



# Feasibility Of One-Dedicated-Lane Bus Rapid Transit/Light-Rail Systems And Their Expansion To Two-Dedicated-Lane Systems: A Focus On Geometric Configuration And Performance Planning



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**MTI REPORT 08-01**

**FEASIBILITY OF ONE-DEDICATED-LANE  
BUS RAPID TRANSIT/LIGHT-RAIL SYSTEMS  
AND THEIR EXPANSION TO  
TWO-DEDICATED-LANE SYSTEMS:  
A FOCUS ON GEOMETRIC CONFIGURATION  
AND PERFORMANCE PLANNING**

**March 2009**

**H.-S. Jacob Tsao, Wenbin Wei, and Agus Pratama**

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Mineta Transportation Institute  
College of Business  
San José State University  
1200 New Jersey Avenue, SE  
San José, CA 95192-0219  
Tel (408) 924-7560  
Fax (408) 924-7565  
E-mail: [mti@mti.sjsu.edu](mailto:mti@mti.sjsu.edu)  
<http://transweb.sjsu.edu>

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## EXECUTIVE SUMMARY

Public transportation is perhaps one of the few sustainable transportation solutions for urban or suburban areas in the future, particularly given the steady increase in energy demand by the world's developed nations, diminishing fossil-fuel reserves, absence of clearly promising alternative fuels for transportation, rising fuel costs, mounting environmental concerns, and the energy and environmental pressures imposed by the fast development of China, India, Brazil, Russia and other countries.<sup>1,2</sup> Light-rail or subway systems are the mass transit systems used in most developed countries; Bus Rapid Transit (BRT) is a new mass transit system that has been adopted by developed countries, such as the United States, and developing countries, such as China and Brazil.<sup>3, 4</sup>

To some developed countries such as the United States, a major problem with public transportation in most urban or suburban areas is the low population density, which is partially influenced by the prevailing zoning regulations, which are influenced by market demand and other social issues. The vast majority of U.S. urban or suburban areas have been designed with the expectation that automobiles will be people's primary means of mobility. In many urban-sprawl areas, the current demand for bus transportation or light-rail is so low that dedicating two full lanes in a roadway median (except at at-grade intersections) and the space needed for bus stops for the exclusive use of buses or light-rail trains has led, or would lead, to underuse of the right-of-way, usually amid heavy automobile traffic during the peak commute hours. Such underuse has caused or could cause the driving public to resent public transportation. Transit-oriented development (TOD) has been promoted as a way to increase demand for transit and reduce automobile use. Without a good transit system, TOD may be difficult to implement; without TOD, it may be difficult to build a good transit system. This can be viewed as a chicken-and-egg problem.

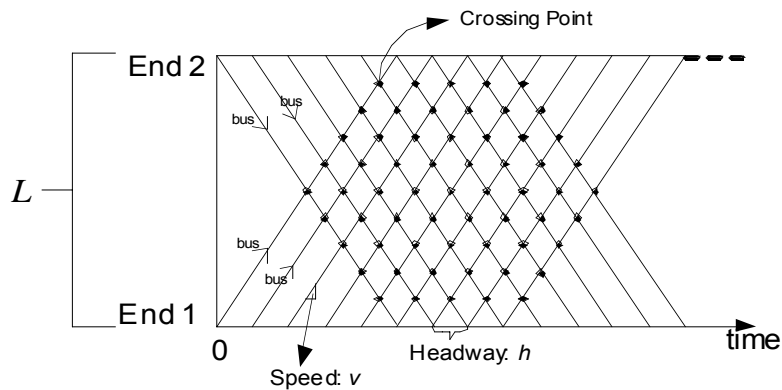
Many urban and suburban commute corridors lack a right-of-way sufficient for a BRT or light-rail system using two dedicated lanes. For example, sections of the Eugene-Springfield (Oregon) BRT, the EmX Green Line, are implemented with only one dedicated lane. However, the crossing of buses traveling in opposite directions on this BRT is accommodated at a bus station that occupies three lanes, with one dedicated bus lane for each of the two directions and a passenger platform between the two dedicated lanes.<sup>5</sup> To developing countries such as China, the construction and development of BRT or a light-rail system requires a significant investment, which can be a big hurdle to the development of an efficient mass transit system.

These chicken-and-egg, right-of-way, and cost problems motivated our concept of a one-dedicated-lane BRT or light-rail system. This would use only one dedicated but dynamically reversible lane in the median of an arterial serving a busy commute corridor, significantly reducing the land and funding required. We believe that it provides a real hope for the construction of an efficient and effective public transportation system in both developed and developing countries. For busy commute corridors that have sufficient right-of-way but do not have enough demand to warrant dedication of two mixed-use lanes to public transportation, the proposed system could be a useful intermediate step

toward a two-dedicated-lane system because of its potential for facilitating transit-oriented development.

This project has sought to identify and resolve major implementation issues and to assess the practicality and performance of the proposed system. A key issue is the crossing of buses traveling in opposite directions, which requires space. The focus is on geometric configuration and performance planning.

To illustrate the crux of the operation of the proposed system, consider the following simple and idealized time-space diagram, with the time a bus spends on passenger activities not explicitly shown but absorbed in the bus travel time.



**Figure 1 A simple space-time diagram for study of operational performance**

This diagram shows how buses of a constant headway  $h$  traverse through the route between End 1 and End 2, in the same or opposite directions. Crossing of buses in opposite directions takes place at the crossing points, which may be stand-alone crossing spaces dedicated to such crossings, without any passenger activities, or a combined facility with crossing and passenger activities integrated in one space. There may be more crossing spaces than what are shown as crossing points in the diagram. Additional crossing spaces can be used to help a bus return to schedule after a delay. Any segment of the dedicated lane that spans two adjacent crossing spaces can accommodate traffic in only one direction at any time, with the two opposite directions alternating through time.

The following are the most critical new issues for this project:

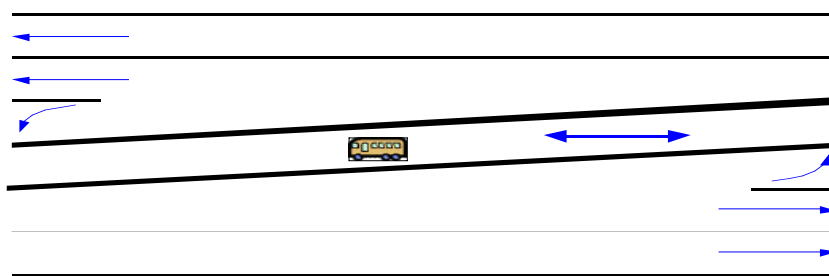
- how to accommodate crossing of buses traveling in opposite directions, which requires an additional lane beyond the dedicated lane, without negative impact on the traffic using the regular mixed-flow lanes
- how to accommodate passenger access, boarding, and alighting with a minimum amount of space
- whether such accommodation can be provided at a sufficient number of locations in regular distance intervals so as to provide the same or similar level of service that is achievable by conventional counterparts

The basic idea behind the proposed concept is simple: bus crossing is accommodated on the otherwise unused or underused median space resulting from provision of the left-turn lanes. Although not necessary, some left-turn lanes can be sacrificed for bus

stops. Crossing spaces can be strategically placed to achieve desired bus headway and travel time. As in the case of a two-dedicated-lane BRT system, bus speed profiles can be adjusted and transit signal priority employed to maximize adherence to the schedule.

This project demonstrates the practicality of the proposed system with many conceptual design options and geometric-configuration sketches for the bus stop and crossing space, along with a deterministic study of the system performance in terms of travel speed, headway of operations, distance between two neighboring crossing spaces, and the number of crossing spaces. To ensure practicality, implementation of such a system on an existing corridor was studied.

Figure 2 illustrates how a dedicated lane can fit into the median of an arterial. The slanting shown in the figure is important and saves one lane's worth of right-of-way. If the dedicated lane is straight with respect to the direction of the roadway and two left-turn lanes are to be provided, then more space will be required beyond the one additional lane dedicated to the BRT. Note that such slanting can save one lane's worth of right-of-way for a corresponding two-dedicated-lane BRT system. Such slanting can save one lane for the current design of the East Bay BRT, which calls for dedicating two straight lanes.

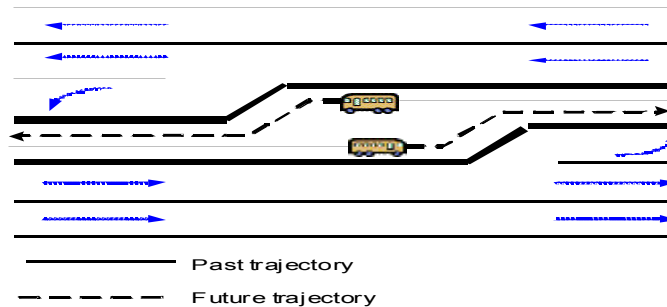


**Figure 2 One lane dedicated to alternating two-way traffic**

Although the right-of-way of an arterial serving a busy corridor may be wider at intersections with major cross streets, the total width of the right-of-way dedicated to the rest of the roadway of such a corridor changes only occasionally. The width of a section between two adjacent intersections equipped with one left-turn lane each (for opposite directions) typically remains constant. When compared to the length of such a section, a typical left-turn lane is rather short. Therefore, a significant amount of median space tends to exist along the roadway between two such adjacent intersections, and such median space tends to be noncritical or even unnecessary for traffic purposes. Such median space is typically occupied with plants or is used for left turns into store parking lots. In this report, we refer to unused or underused median space as “unused median space.”

Because of the frequent availability of left-turn lanes at intersections and the typically constant section width, much unused median space exists throughout the arterial of a busy commute corridor. We capitalize on the existence of such unused median spaces and use them for bus crossings, as shown in Figure 3.

The crossing space can be expanded to accommodate a bus stop also, with the possibility of sacrificing one or both of the two left-turn lanes.



**Figure 3 A space dedicated to crossing operation**

A key performance issue is the timely crossing of buses traveling in opposite directions. The proposed system requires that a minimum set of crossing spaces be placed strategically so that the travel time  $T$  between any adjacent pair of such spaces is the same as that between any other such pair. Consequently, the minimum headway  $h$  is equal to twice the constant travel time  $T$ , that is,  $h = 2T$ . Moreover, any delay of any bus in reaching a crossing space will cause a delay not only in the schedule for buses traveling in its direction but also a delay to the schedule of buses traveling in the opposite direction. This project conducted a deterministic study, which demonstrated good performance.

This project also proposed ways to implement a two-dedicated-lane BRT or light-rail system with minimum right-of-way width, and ways to expand a one-dedicated-lane system to two dedicated lanes. All BRT or light-rail systems already implemented or intended for possible future implementation in the United States have two dedicated traffic lanes, except for small portions where geometrical constraints are severe. A space equivalent to four traffic lanes also is dedicated to accommodating a bus stop. We proposed implementations of such two-dedicated-lane systems that require a space equivalent to only three lanes at a bus stop, based on two key ideas proposed for a one-dedicated-lane system. The three-lane requirement is particularly advantageous over its four-lane counterpart because many busy commute corridors are served by a thoroughfare with a right-of-way that is equivalent to seven traffic lanes: two traffic lanes for each direction, one parking lane for each direction, and one left-turn lane in the median used for the appropriate direction. Dedicating three lanes for the BRT or light-rail system still leaves two lanes per direction, while dedicating four lanes results in either an asymmetric roadway geometry or no more than one lane for each direction.

The chicken-and-egg problem, among other issues, motivated our proposal for a one-dedicated-lane BRT or light-rail system. This project also proposed ways to expand the proposed one-dedicated-lane systems to two-dedicated-lanes systems, as the demand for public transportation grows and dedication of one additional lane is accepted by the general public.

A key remaining issue is to ensure on-time crossing, particularly to recover from a delay of a bus, by developing detailed operating rules, including speed-profile control (SPC) and transit signal priority (TSP), and by using computer simulation to study and compare the stochastic performance of the rules. Control of bus speed profile requires technologies that monitor the current position, the current speed, and the schedule of a



bus; communicate the information to a system control system; compute the required speed profile adjustment; and convey the resulting instructions to the driver and the on-board bus control system, if so equipped. A research proposal about this important future research topic, entitled *Developing Operating Rules and Simulating Performance for One-Dedicated-Lane Bus Rapid Transit/Light Rail Systems*, has been submitted to California Partners for Advanced Transit and Highways (PATH), in response to PATH's Call for Proposal for the fiscal year of 2007-2008, under the category of Innovative Research Topics, for possible seed funding of \$25K. The proposal has been approved by PATH and Caltrans, and a contract has been issued, with a target performance period of October 1, 2008 through September 2009.



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## INTRODUCTION

Public transportation is perhaps one of the few sustainable transportation solutions for urban or suburban areas in the future, particularly given the steady increase in energy demand by the world's developed nations, diminishing fossil-fuel reserves, absence of clearly promising alternative fuels for transportation, rising fuel costs, mounting environmental concerns, and the energy and environmental pressures imposed by the fast development of China, India, Brazil, Russia and other countries.<sup>5,6</sup> Light-rail or subway systems are the mass transit systems used in most developed countries; Bus Rapid Transit (BRT) is a new mass transit system that has been adopted by both developed countries, such as the United States, and developing countries, such as China and Brazil.<sup>7,8</sup>

To some developed countries such as the United States, a major problem with public transportation in most urban or suburban areas is the low population density, which is partially influenced by the prevailing zoning regulations, which have been influenced by market demand and other social issues. The vast majority of U.S. urban or suburban areas have been designed with the expectation that automobiles will be people's primary means of mobility. In many urban-sprawl areas, the current demand for bus transportation or light-rail is so low that dedicating two full lanes in a roadway median (except at at-grade intersections) and the space needed for bus stops for the exclusive use of buses or light-rail trains has led, or would lead, to underuse of the right-of-way, usually amid heavy automobile traffic during the peak commute hours. Such underuse has caused or could cause the driving public to resent public transportation. Transit-oriented development (TOD) has been promoted as a way to increase demand for transit and reduce automobile use. Without a good transit system, TOD may be difficult to implement; without TOD, it may be difficult to build a good transit system. This can be viewed as a chicken-and-egg problem.

Many urban and suburban commute corridors lack a right-of-way sufficient for a BRT or light-rail system using two dedicated lanes. For example, sections of the Eugene-Springfield (Oregon) BRT, the EmX Green Line, are implemented with only one dedicated lane. However, the crossing of buses traveling in opposite directions on this BRT is accommodated at a bus station that occupies three lanes, with one dedicated bus lane for each of the two directions and a passenger platform between the two dedicated lanes.<sup>9,10,11</sup> To developing countries such as China, the construction and development of BRT or a light-rail system requires a significant investment, which can be a big hurdle to the development of an efficient mass transit system.

These chicken-and-egg, right-of-way, and cost problems motivated our concept of a one-dedicated-lane BRT or light-rail system. It would use only one dedicated but dynamically reversible lane in the median of an arterial serving a busy commute corridor, significantly reducing the land and funding required. We believe that it provides a real hope for the construction of an efficient and effective public transportation system in both developed and developing countries. For busy commute corridors that have sufficient right-of-way but do not have enough demand to warrant dedication of two mixed-use lanes to public transportation, the proposed system could be a useful intermediate step

toward a two-dedicated-lane system because of its potential for facilitating transit-oriented development.

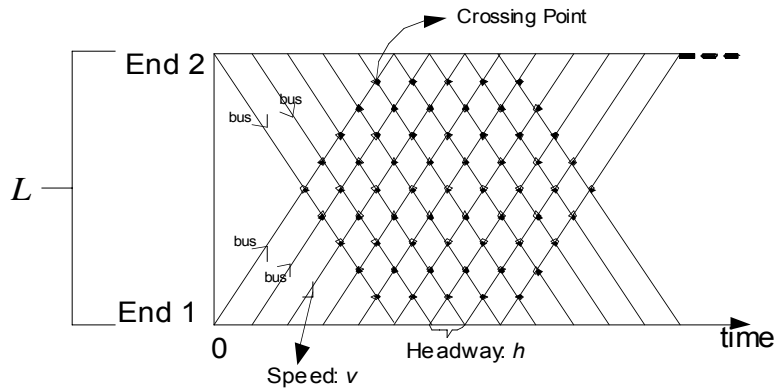
The rest of this paper consists of two main parts, followed by concluding remarks. The next section, “[Feasibility of One-Dedicated-Lane Bus Rapid Transit/Light-Rail Systems](#),” proposes this concept of a BRT or light-rail system. Based on two key ideas proposed in that section, “[Space Minimization for Implementing Dedicated Bus Rapid Transit/Light-Rail System](#)” first addresses how to implement a two-dedicated-lane BRT or light-rail system with minimum right-of-way width, then proposes ways to expand a one-dedicated-lane system to two dedicated lanes. Because of the unconventional nature of the proposed concepts, a research task was to solicit comments and critiques from BRT experts, including researchers and practitioners. “[Conclusions](#)” includes these comments and discusses important topics for future research.

The section on feasibility studies the operational feasibility of using only one dedicated but dynamically reversible lane to provide two-way BRT or light-rail services at the same or similar service levels as those achievable with two dedicated lanes, along the median of a busy commuter corridor with regular provision of left-turn lanes. A main goal of this line of research is to develop a methodology that can be used to determine if such a one-dedicated-lane BRT or light-rail system would be feasible and practical for any given urban corridor, and, if so, how it should be designed and operated to achieve the highest possible performance. Because of space limitations, this paper only identifies and resolves major implementation issues about geometric configuration and performance planning.

The key feature of the proposed one-dedicated-lane BRT or light-rail system is the use of one lane to accommodate two-way bus traffic except at locations where two buses (or two bus clusters) or two light-rail trains traveling in opposite directions cross each other, or at locations where passengers access, board, or alight a bus or light-rail train. We refer to the former locations as crossing locations and a space used to accommodate such crossing as a crossing space. We refer to the latter locations as a bus stop as usual.

To illustrate the crux of the operation of the proposed system, consider the simple and idealized time-space diagram of [Figure 4](#), with the time a bus spends on passenger activities not explicitly shown but absorbed in the bus travel time. This diagram shows how buses of a constant headway  $h$  traverse through the route between End 1 and End 2, in the same or opposite directions. The crossing of buses in opposite directions takes place at the crossing points, which may be a standalone crossing space dedicated only to such crossing (without any passenger activities) or a combined facility with crossing and passenger activities integrated in one space. As will be explained later, there may be more crossing spaces than shown as crossing points in the diagram. The additional crossing spaces can be used to help a bus return to schedule after a delay. Any segment of the dedicated lane that spans two adjacent crossing spaces can accommodate traffic in only one direction at any time, with the two opposite directions alternating through time.

The following are the most critical new issues for this project:



**Figure 4 A simple space-time diagram for study of operational performance**

- how to accommodate crossing of buses traveling in opposite directions, which requires an additional lane beyond the one dedicated lane, without negative impact on the traffic using the regular mixed-flow lanes
- how to accommodate passenger access, boarding, and alighting with a minimum amount of space
- whether such accommodation can be provided at a sufficient number of locations in regular distance intervals so as to provide the same or similar level of service that is achievable by conventional counterparts

The basic idea behind the proposed concept is simple: bus crossing is accommodated on the otherwise unused or underused median space resulting from provision of the left-turn lanes. Although not necessary, some left-turn lanes can be sacrificed for bus stops. Crossing spaces can be strategically placed to achieve desired bus headway and travel time. As in the case of a two-dedicated-lane BRT system, bus speed profiles can be adjusted and transit signal priority employed to maximize adherence to the schedule.

To help us develop a practical operating concept and thus maximize the value of this study, the corridor served by the Blue Line of the Valley Transportation Authority (VTA) Light Rail of Santa Clara County, California (between the Alum Rock station and the Santa Teresa Station) is used as the reference corridor for a reality check. We study in more detail the segment between Downtown San Jose and the Tasman Station in Milpitas because this segment is also traveled by the Green Line of the light-rail system, necessitating a shorter headway for this segment. Supporting two-way traffic on only one dedicated lane throughout virtually the entire length of a corridor necessitates major changes to both the passenger operation and the crossing operation.

**“Space Minimization for Implementing Dedicated Bus Rapid Transit/Light-Rail System”** first addresses how to implement a two-dedicated-lane BRT or light-rail system with minimum right-of-way width, then proposes ways to expand a one-dedicated-lane system to two dedicated lanes. All BRT or light-rail systems already implemented or intended for possible future implementation in the United States involve two dedicated traffic lanes. A space equivalent to four traffic lanes is dedicated for accommodating a bus stop. We propose implementations of such two-dedicated-lane systems that require a space equivalent to only three lanes at a bus stop, based on two key ideas proposed

for a one-dedicated-lane system. The three-lane requirement is particularly advantageous over its four-lane counterpart because many busy commuter corridors are served by a thoroughfare with a right-of-way equivalent to seven traffic lanes: two traffic lanes for each direction, one parking lane for each direction, and one left-turn lane in the median used for the appropriate direction. Dedicating three lanes for the BRT or light-rail system still leaves two lanes per direction, while dedicating four lanes results in either an asymmetric roadway geometry or no more than one lane for each direction.

The chicken-and-egg problem, among other issues, motivated our proposal for a one-dedicated-lane BRT or light-rail system.

The rest of this paper is organized in the following sections:

[“Feasibility of One-Dedicated-Lane Bus Rapid Transit/Light-Rail Systems,” page 11](#)

[“Space Minimization for Implementing Dedicated Bus Rapid Transit/Light-Rail System,” page 33](#)

[“Conclusions,” page 43](#)

[Appendix A, “Santa Clara Valley Transportation Authority \(VTA\) Light-Rail System Map,” page 49](#)

[“Endnotes,” page 51](#)

[“Abbreviations and Acronyms,” page 53](#)

[“Bibliography,” page 55](#)

[“About the Authors,” page 57](#)

[“Peer Review,” page 59](#)

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# FEASIBILITY OF ONE-DEDICATED-LANE BUS RAPID TRANSIT/LIGHT-RAIL SYSTEMS

## A Focus on Geometric Configuration and Performance Planning

This section is organized as the following subsections:

- “[Problem Definition](#)” defines the problem addressed in this section, including a description of our study approach and the scope of this paper.
- “[Options for Geometrical Design of Bus Stop and Crossing Space](#)” discusses five dimensions of options for geometrical design of stops and crossing spaces.
  - “[Geometric Designs for a Space Dedicated to the Crossing Operation](#)” describes the conceptual design of a standalone crossing space that does not support passenger accessing, boarding, or alighting.
  - “[Geometric Design for a Standalone Bus Stop Dedicated to Passenger Operation](#)” discusses the conceptual design for a standalone bus stop that does not support traffic crossing.
  - “[Geometric Designs for a Space Accommodating Both Crossing and Passenger Operations](#)” addresses the conceptual design of a more complex geometric configuration where both traffic crossing and passenger accessing, boarding, and alighting are accommodated at one location.
- “[Operational Performance](#)” addresses the headway or frequency of service that can be accommodated on the proposed system, with a deterministic analysis.
- “[Assessment of Feasibility for Implementation on Existing Corridors](#)” briefly describes the corridor served by the segment of the Blue Line of the VTA light-rail system between Downtown San Jose and the Alum Rock station. It demonstrates the practicality and space saving associated with implementing a one-dedicated-lane BRT or light-rail system if the current light-rail right-of-way along the median of the corridor were to be used for a one-dedicated-lane BRT or light-rail system.
- “[Summary](#)” summarizes the discussion in this section.

### PROBLEM DEFINITION

We are not aware of any previous studies about the feasibility of providing two-way bus or light-rail traffic along the entire length of an urban or suburban commuter corridor with only one dedicated but dynamically reversible lane in the median or any other part of the roadway, although two-way traffic of a short segment of an existing BRT system in Oregon has been accommodated with only one dedicated lane.<sup>12</sup>

Designing a practical system of this type and optimizing its performance requires a great deal of research and development effort. First, the practicality and performance of such a system hinges on its interaction with the surrounding traffic, especially traffic signaling. To limit the scope of this paper, we focus on a *closed system* and ignore the surrounding traffic and the effect of signaling on the system performance. Transit signal priority (TSP) for a one-dedicated-lane BRT or light-rail system is a worthy research subject but is beyond the scope of this paper. We also discuss geometric configuration and performance planning.



The proposed concept works for both BRT systems and light-rail systems. In this discussion, we address only BRT explicitly, but the same information applies to light-rail systems unless an exclusion is pointed out. As mentioned earlier, we check our conceptual designs for realism against a reference corridor—the corridor served by the Valley Transportation Authority (VTA) Light Rail of Santa Clara County of California between the Alum Rock station and the Santa Teresa Station, particularly the segment between Downtown San Jose and the Tasman Station in Milpitas.

In all major commuter corridors in the San Francisco Bay Area, including the San Francisco Peninsula, South Bay (including San Jose), and East Bay (including Oakland), the corresponding arterials are equipped with frequent left-turn lanes throughout the corridors, although exceptions exist. This allocation of space for facilitating left-turning traffic makes sense because typically there is a significant amount of left-turning traffic on a busy commuter corridor. Some of the busiest intersections are equipped with multiple left-turn lanes, depending on the direction.

Although the right-of-way may be wider at intersections with major cross streets, the total width of the right-of-way dedicated to the rest of the roadway of such a corridor changes only occasionally. In particular, the width of a section between two adjacent intersections equipped with one left-turn lane each for opposite directions typically remains constant. Compared to the length of such a section, a typical left-turn lane is rather short. Between two such adjacent intersections, there is usually a significant amount of median space along the roadway that tends to be noncritical or even unnecessary for traffic purposes. Such median space may be occupied with plants or used for left turns into store parking lots. We refer to such unused or underused median space as unused median space. As a result of the frequent availability of left-turn lanes at intersections and the typical constant section width, typically there is much unused median space throughout the arterial of a busy commuter corridor. In this paper, we focus on corridor arterials that are equipped with left-turn lanes throughout and capitalize on the existence of such unused median space. We also address situations where the required right-of-way does not exist for such left-turn lanes.

In a closed system, a system using one dedicated lane has one other major operation beyond passenger accessing, boarding, and alighting: the crossing of buses traveling in opposite directions. Here we refer to passenger accessing, boarding, and alighting simply as passenger operation. New geometrical designs are required to support two-way traffic on one dedicated lane. [“Options for Geometrical Design of Bus Stop and Crossing Space”](#) on [page 13](#) discusses in detail five dimensions of options for the geometrical design. One option from each dimension must be selected to constitute a geometrical design. For implementation selection, some such designs will be discussed in [“Geometric Designs for a Space Dedicated to the Crossing Operation”](#) ([page 17](#)), [“Geometric Design for a Standalone Bus Stop Dedicated to Passenger Operation”](#) ([page 18](#)), and [“Geometric Designs for a Space Accommodating Both Crossing and Passenger Operations”](#) ([page 20](#)). Several specific designs will be selected in [“Assessment of Feasibility for Implementation on Existing Corridors”](#) ([page 25](#)) for implementation at specific locations on the reference corridor.

To study the operational performance, this paper focuses on mainline operations. None of the buses considered here go off the mainline to collect or distribute local passengers. We assume that no bus overtaking or passing is allowed, that is, two buses cannot travel



in the same direction and cross paths. Therefore, the main design issue is how to make two buses traveling in opposite directions pass each other only at a crossing space without undue delays to the buses involved. To illustrate the crux of the operational issues associated with this one-dedicated-lane BRT, we focus on mainline buses, ignore the surrounding traffic, and effectively assume perfect transit signal priority, as mentioned earlier.

In “[Operational Performance](#)” (page 22) we analyze an idealized corridor and build the relationship among the travel speed of bus, headway of bus dispatching, distance between two neighboring crossing spaces, and capacity of the one-dedicated-lane system. In “[Assessment of Feasibility for Implementation on Existing Corridors](#)” (page 25), we study the performance of the proposed system implemented on the reference corridor.

This section ends with the “[Summary](#)” on page 32.

## **OPTIONS FOR GEOMETRICAL DESIGN OF BUS STOP AND CROSSING SPACE**

This section introduces various design options along five different design dimensions. These options will be illustrated in this and later sections.

There are at least three strategies for locating the crossing and the passenger operations:

- Completely segregate the crossing operation from the passenger operation; never accommodate the crossing operation and the passenger operation in one integrated facility.
- Completely integrate the crossing and passenger operations; in particular, crossing always takes place at a bus stop.
- Allow the crossing operation to take place either at a bus stop or at a location away from any bus stop.

The strengths and weaknesses of these three strategies hinge on the site and other considerations. To support all three possible strategies, three different operational implementations are required: standalone crossing space without passenger accessing, boarding, and alighting activities; a standalone bus stop without traffic crossing; and an integrated bus stop and crossing space. These are the three design options for the functional dimension.

Since the one-dedicated-lane system is implemented in the median of an arterial, passengers must enter and exit a bus stop through an intersection. (We assume no elevated structure is constructed for such purposes.) A standalone crossing space does not involve an entrance or an exit.

There are three design options for locating a bus stop, as a standalone bus stop or as part of an integrated facility accommodating both passenger and crossing operations:

- Confine it within one section and provide two passenger entrances/exits, one on each side of the section.

- Confine it within one section but provide one passenger entrance/exit, on only one side of the section.
- Allow it to span the two sections adjacent to an intersection and provide two passenger entrances/exits, one on each side of the intersection along the corridor.

These three options constitute the entrance-exit dimension.

The main arterial of a busy commuter corridor typically has frequent left-turn lanes. The configurations for a bus stop, a crossing space, or their integration that are proposed in the rest of the paper take full advantage of the almost ubiquitous presence of left-turn lanes. As a practical matter, however, geometric designs suited for sections without such left-turn lanes are required. The two options regarding the availability of a left-turn lane in the current roadway configuration constitute the left-turning dimension. If there is no left-turn lane at a particular location being considered as a candidate for one of these three facilities, one lane alone is not sufficient and an additional space (an additional lane, in our terminology) must be made available.

Another consideration is how a proposed bus stop or an integrated bus stop and crossing space influences the left-turning movement at an intersection. In some configurations, one or two of the left-turn lanes are sacrificed to accommodate a bus stop or an integrated bus stop and crossing space. This information will be provided as an extension to either of the two options of this dimension.

The prevailing mode of bus operations in the United States requires that the driver monitor proper payment by the riders; therefore, passengers must board a bus from the front door, which is at the right-hand side of the bus. For a forward-looking operational concept such as the one being proposed, different options should also be considered. An alternative is to equip the bus with doors on both sides. This may require that the passenger pay the bus fare when entering a bus stop and that the stop be equipped with a designated space and the corresponding physical barriers for fare collection. These two options constitute the fare-collection or doorside dimension.

Finally, the length of a section may matter, particularly for the two design options involving the confinement of the bus stop (or an integrated bus stop and crossing space) within one section in the entrance-exit dimension. A section may be long or short, and these two options constitute the section-length dimension. For a short section, providing two entrances/exits (one on each side of the section) could be a matter of choice. For a long section, providing one entrance and exit on each end of the section may be a waste of space and resources, and may require excessive walking. Also, the short length of the section may limit viable options along the functional dimension. Therefore, the section-length dimension is not completely independent of the entrance-exit dimension, nor is it completely independent of the functional dimension. Note that a crossing space can be provided at any section that is sufficiently long and equipped with one left-turn lane on each side. The more such crossing spaces, the less traffic-delay penalties.

In summary, the five dimensions of design options for a bus stop and crossing space are:

- *Functional dimension*—three options:
  - standalone crossing space
  - standalone bus stop
  - integrated bus stop and crossing space

The next three subsections are devoted to the following three options, respectively.

- *Entrance-exit dimension.* A standalone crossing space does not require an entrance and exit. A standalone bus-stop or an integrated bus stop and crossing space can have one of the following three options:
  - one section and two passenger entrances/exits (one on each side of the section)
  - one section and one passenger entrance/exit (on only one side of the section)
  - two sections adjacent to an intersection and two passenger entrances/exits (one on each of the two sides of the intersection along the corridor)

Note that a midblock entrance/exit may also work for a standalone bus stop. Since bus crossing will take place in midblock, such entrance/exit may not work well for an integrated bus stop and crossing space.

- *Left-turning dimension*—two options
  - a left-turn lane at the two ends of the section
  - no left-turn lane at the two ends of the section
- *Fare-collection (door-side) dimension.* This refers to the minimum requirement for the equipment and has two options:
  - buses equipped with doors only on the right-hand side, the standard for bus systems in the United States
  - buses equipped with doors on both sides, the standard for light-rail systems or any other commuter rail systems

This is a major difference between bus and light-rail systems. When doors are provided on both sides of a bus, those on the driver's side may or may not be used, at least for some bus stops.

- *Section-length dimension*—two options: long or short.

Based on these design dimensions and options, several configurations exist. Many have been developed and corresponding sketches drawn. Of these configurations and sketches, those discussed in this paper are useful for a large number of real-world implementations or are suitable for possible implementation on the reference corridor. Because of the focus on geometric configuration and performance planning, we do not address bus features in detail. However, it is important to note two things: buses need to have low floors and platforms need to be high to allow level boarding, and fares will need to be prepaid. These factors help keep buses on schedule, which is very important. We do not address spacing of bus stops in detail either, but bus stops, like their conventional counterparts, should be about 0.5 to 1 mile apart.

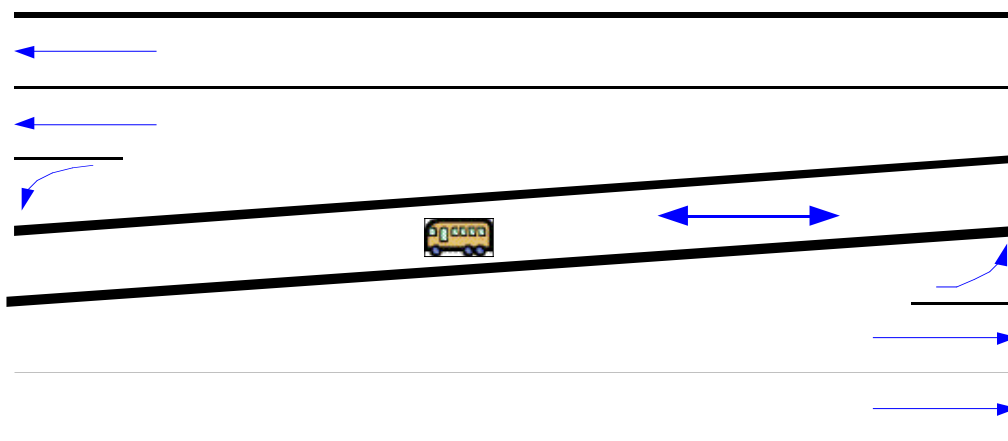
The remainder of this subsection presents seven geometric configurations in the form of geometric sketches and their variations. These are included based on the following criteria:

- Default options were selected for two dimensions. All the configurations discussed in the following sections involve a left-turn lane on each of the two ends of a section or on each of the two sides of an interaction. The doors-on-right-hand-side option of the fare-collection dimension is the default.
- Every option of every dimension should be part of an included configuration, except the option of not having a left-turn lane. (It is straightforward to extend the included configurations to suit a situation where such a left-turn lane is absent.) This is done to

ensure that each such option is illustrated, and that its role in the design and its possible interaction with other design options of the same or different dimensions are clarified in the context of a complete design. For example, the doors-on-both-sides option of the fare-collection dimension is part of Configuration 4, discussed in “Geometric Design for a Standalone Bus Stop Dedicated to Passenger Operation”.

- Because of the importance of the three options in the functional dimension and for ease of discussion, the next three sub-sections are organized according to the three options of functional dimension.

Before discussing specific configurations for bus stops and crossing spaces, we provide a sketch of a geometric configuration (Configuration 1 shown in Figure 5) that has one lane dedicated to alternating traffic of the two opposite directions and does not support passenger or crossing operations. When a section is not long enough, traffic crossing cannot be accommodated. To accommodate the one dedicated lane subject to the space restrictions imposed by the requirement of one left-turn lane at both ends of the section, the dedicated lane needs to be slanted or slightly S-shaped with respect to the longitudinal direction of the roadway, as shown in Figure 5.



**Figure 5 Configuration 1: One lane dedicated to alternating two-way traffic**

No crossing and no stop; no entrance-exit; left-turning; doors on one side or both; section not sufficiently long for crossing

Note that the slanting shown in Figure 5 saves one lane’s worth of right-of-way. If the dedicated lane is straight with respect to the direction of the roadway and two left-turn lanes are to be provided, more space will be required beyond the one additional lane dedicated to the BRT and more unused median space will be introduced. Such slanting can also save one lane’s worth of right-of-way for a two-dedicated-lane BRT system.

This and all configurations proposed later illustrate the proposed operational concept. For ease of comparison, each sketch shows traffic moving along the east-west direction, that is, horizontally between the left- and right-hand sides of the diagram. In addition, two lanes are provided for through traffic for each of the two directions. The width of right-of-way is measured in the unit of a traffic lane, regardless of whether the traffic lane is a through lane for regular traffic, a left-turn lane, or a dedicated bus lane. A passenger platform, whether it is dedicated to use only by passengers heading in one direction or is

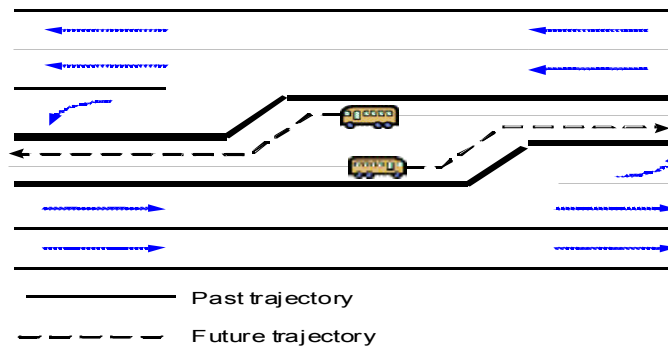
shared between passengers heading in both directions, is treated as being as wide as a traffic lane. We ignore possible curbside parking altogether.

Each sketch details the design options below the figure caption. Such sketches will need to be expanded into detailed geometric designs in the future, according to related standards. Detailed standards for designing bus stops and other roadway features can be found in the existing literature.<sup>13,14,15</sup>

### Geometric Designs for a Space Dedicated to the Crossing Operation

This section focuses on the conceptual design of a standalone crossing space, that is, a crossing space that is not integrated with a bus stop and not collocated with a bus stop in the same section or at two opposite sides of an interaction. The length of this crossing space depends on space availability. The longer the section is, the more efficient the crossing of two buses traveling in opposite directions could be. This efficiency can be measured by bus waiting time and the maximum number of buses that can cross each other at the crossing space. If the section is not long enough, such crossing cannot be accommodated.

Configuration 2, shown in Figure 6, demonstrates how the space of a section of a corridor arterial with constant total width and with a left-turn lane at both ends can be efficiently used to support the one dedicated lane required by the proposed BRT system.



**Figure 6 Configuration 2: A space dedicated to crossing operation**

Crossing only; no entrance-exit; left-turning; doors on one side or both;  
section sufficiently long for crossing

This design takes advantage of the situation where sufficient extra space between the two left-turn lanes located on the two ends of a section is unused (or underused) for traffic purposes. Such a space is what we refer to as the unused median space. Such extra spaces could be used as crossing spaces throughout the entire length of the corridor arterial. Capitalizing on such spaces is a key to accommodating two-way bus traffic effectively with only one dedicated lane throughout the entire corridor. However, although such spaces may be underused or unused for traffic purposes, they may be used for other purposes, such as landscaping, which is important for aesthetics.

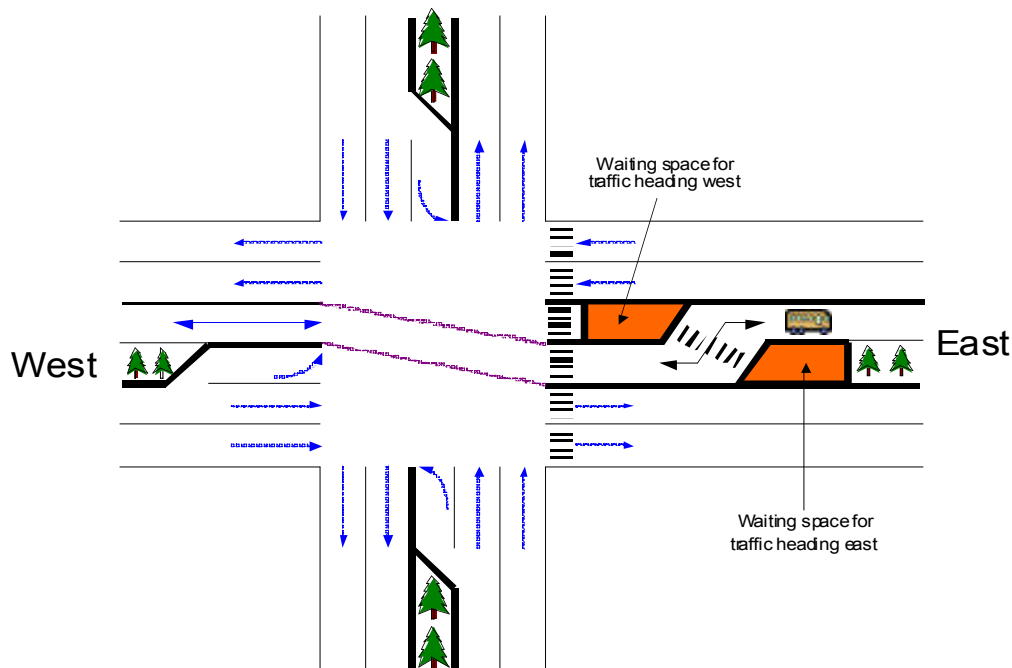
### Geometric Design for a Standalone Bus Stop Dedicated to Passenger Operation

We propose that all bus stops be located adjacent to an intersection with traffic lights so that passengers can easily walk between street sidewalks and the bus stop, and the passengers' movements would have minimum impact on the surrounding traffic. Two such configurations are shown in [Figure 7](#) and [Figure 8](#).

Configuration 3, illustrated in [Figure 7](#), shows a bus stop configuration applicable for a one-dedicated-lane system under the following conditions:

- The bus stop is located within only one section and is equipped with one entrance/exit at one intersection adjacent to the section.
- The current roadway is equipped with one left-turn lane at both sides of the intersection, but the left-turn lane on the side of the bus stop is sacrificed for use as passenger waiting area.
- The bus has doors only on the right-hand side.

Because the bus has doors only on the right-hand side, a waiting area is needed for each of the two traffic directions, as shown in [Figure 7](#). As a result, a passenger walkway that overlaps the dedicated bus lane is required to connect the two passenger waiting areas.



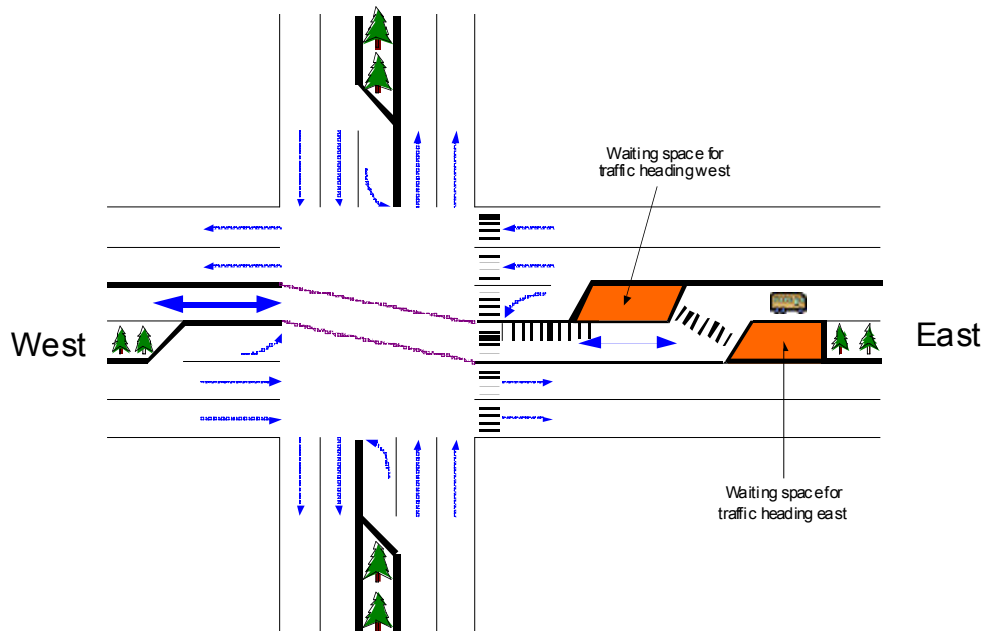
**Figure 7 Configuration 3: A bus stop dedicated to passenger operation on one side of an intersection**

Bus stop only; one section and one entrance-exit; left-turning sacrificed for one side; doors on one side; long or short section

There are other options, of course. For example, if the left-turn lane on the west side of the intersection of Configuration 3 can also be sacrificed, the waiting area for traffic

heading east can be moved to occupy the space thus made available so a passenger walkway would not have to overlap with the dedicated bus lane.

If the left-turn lane on the side of the bus stop is too important to sacrifice, locating a bus stop at this location is necessary, and sufficient space exists, the left-turn lane can be kept and the conflicting passenger waiting area can be moved to the immediate right (or east) of the left-turn lane. However, a passenger walkway between the passenger waiting area and the intersection crosswalk must be equipped, and this second passenger walkway also overlaps with the dedicated lane. This alternative configuration is illustrated in Figure 8. A potential safety issue could occur when passengers alighting a westbound bus are on their way to depart the bus stop but are stuck on the dedicated bus lane because the signal prevents them from crossing the street. This should not occur as long as the passengers begin to depart after the bus has left the stop. Because traffic at this standalone bus stop is one-way and the buses are separated by or close to a fixed headway, this potential conflict should be rare. Stipulating that a bus should always keep a passenger walkway clear should eliminate any safety issue.



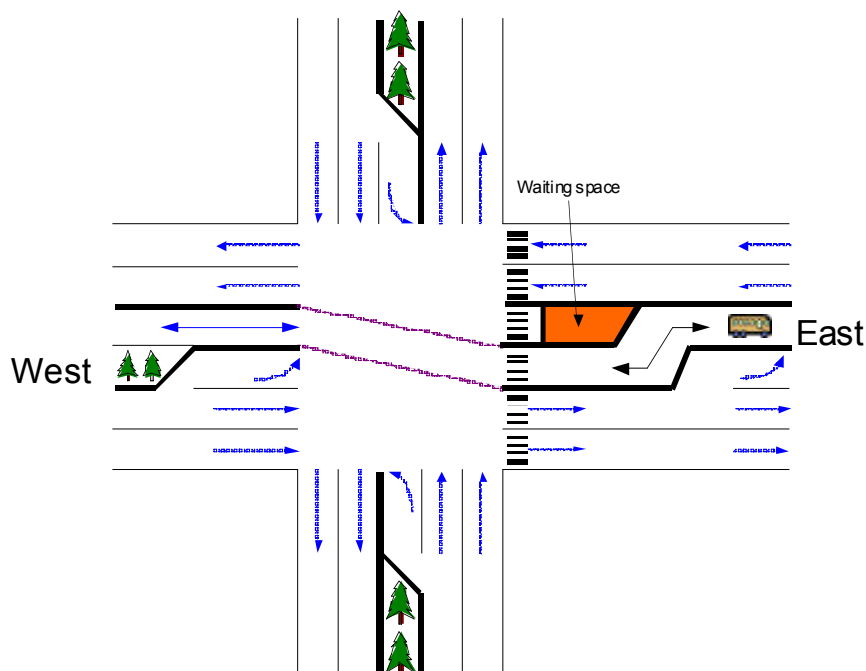
**Figure 8 Configuration 3.a: A bus stop dedicated to passenger operation on one side of an intersection**

Bus stop only; one section and one entrance-exit; left-turning not sacrificed; doors on one side; long or short section

In another variation of Configuration 3, the bus stop is physically separated from the surrounding space with barriers, bus fare is collected as passengers enter the bus stop, and buses are equipped with doors on both sides of the bus. Because the bus has doors on both sides, only one waiting area is needed in the bus stop, which can be used for both directions. Only one left-turn lane is sacrificed, and the passenger walkway does not need to overlap the dedicated bus lane. However, the driver then could not watch the



passengers pay the fare, so passengers must pay the fare before getting on the bus, and the bus stop must be physically separated from the surrounding space. This configuration (Configuration 4) is illustrated in [Figure 9](#).



**Figure 9 Configuration 4: A bus stop dedicated to passenger operation with buses equipped with doors on both sides and with a physically separated waiting area**

Bus stop only; one section and one entrance-exit; left-turning sacrificed on one side; doors on both sides; long or short section

An alternative to Configuration 4 exists in which the left-turn lane on the bus-stop side of the intersection is not sacrificed. The differences, in physical layout and operation, between this alternative and Configuration 4 are analogous to those between Configurations 3 and 3.a. In this alternative configuration, no left-turn lane is sacrificed but a passenger walkway overlapping the dedicated bus lane is required.

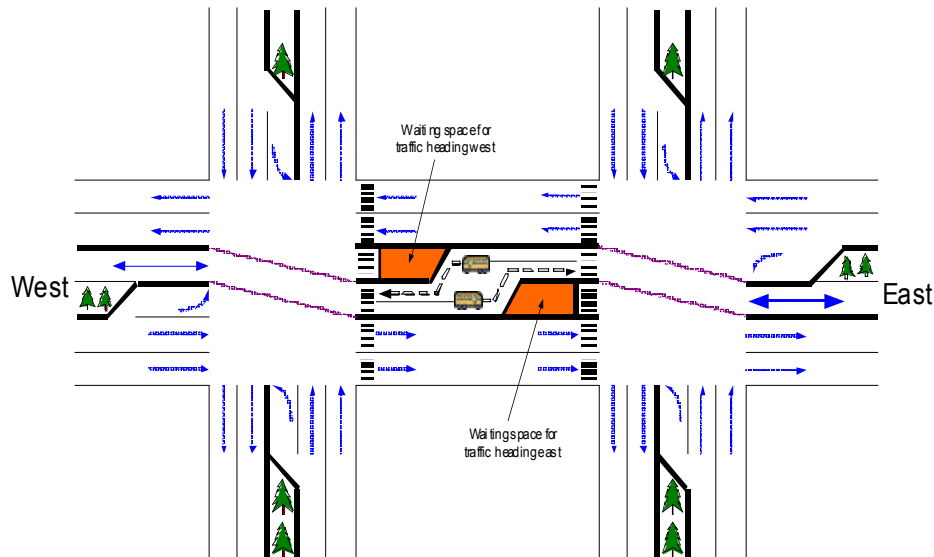
A simple pattern has emerged for these configurations. For systems with bus doors provided on only the right-hand side of the bus (that is, opposite the driver) the number of left-turn lanes sacrificed plus the number of passenger walkways required is two. However, when bus doors are provided on both sides of the bus, the number of left-turn lanes sacrificed plus the number of passenger walkways required is only one.

### **Geometric Designs for a Space Accommodating Both Crossing and Passenger Operations**

An arterial section that is sufficiently long and is equipped with a left-turn lane at both ends can accommodate both passenger and crossing operations. [Figure 10](#) illustrates this configuration (Configuration 5). Note that the two left-turn lanes are replaced with



two passenger waiting areas. As with Configurations 3 and 4, there is an alternative to Configuration 5 in which the two left-turn lanes are not sacrificed. The differences, in physical layout and operation, between this alternative and Configuration 5 are analogous to those between Configurations 3 and 3.a.



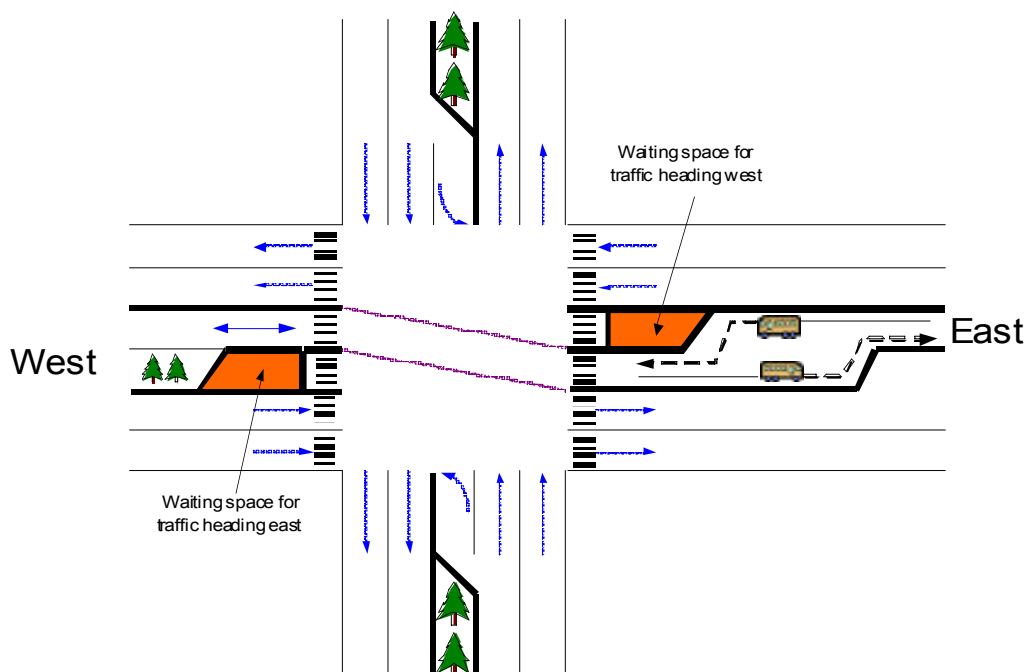
**Figure 10 Configuration 5: A space accommodating both crossing and passenger operations in one section**

Bus stop and crossing; one section and two entrances-exits; left-turning sacrificed on both ends; doors on one side; long section

In this case, both the crossing operation and passenger operation can be accommodated within one section (between two intersections). For safety, buses coming from opposite directions first cross each other at the designated crossing space in the middle of the section, then stop at the designated passenger activity areas at the two ends to let passenger off and on.

Another possible configuration can accommodate both a bus stop and a crossing space on two sides of an intersection where each side is equipped with a left-turn lane. This configuration (Configuration 6) is shown in [Figure 11](#). The key difference between Configurations 5 and 6 is that for the entrance-exit dimension, Configuration 6 has the option of two sections (on two sides of an intersection) and two entrances-exits. This can be viewed as a variation of Configuration 5, in which the passenger waiting area on the east side of the integrated facility is moved to the corresponding position in the section to the west. As for previous configurations, there is an alternative to Configuration 6 in which the left-turn lane on both sides of the intersection is not sacrificed. The differences, in physical layout and operation, between this alternative and Configuration 6 are analogous to those between Configurations 3 and 3.a.

Configuration 3 can be enhanced easily to accommodate a bus stop and a crossing space if there is sufficient extra space. This new configuration (Configuration 7) is illustrated in [Figure 12](#). The only difference between Configurations 3 and 7 is the additional space required in the latter for crossing. If the east end of the integrated bus



**Figure 11 Configuration 6: An integrated bus stop and crossing space located on two sides of an intersection**

Bus stop and crossing space; two sections and two entrances-exits; left-turning sacrificed; doors on one side; long or short section

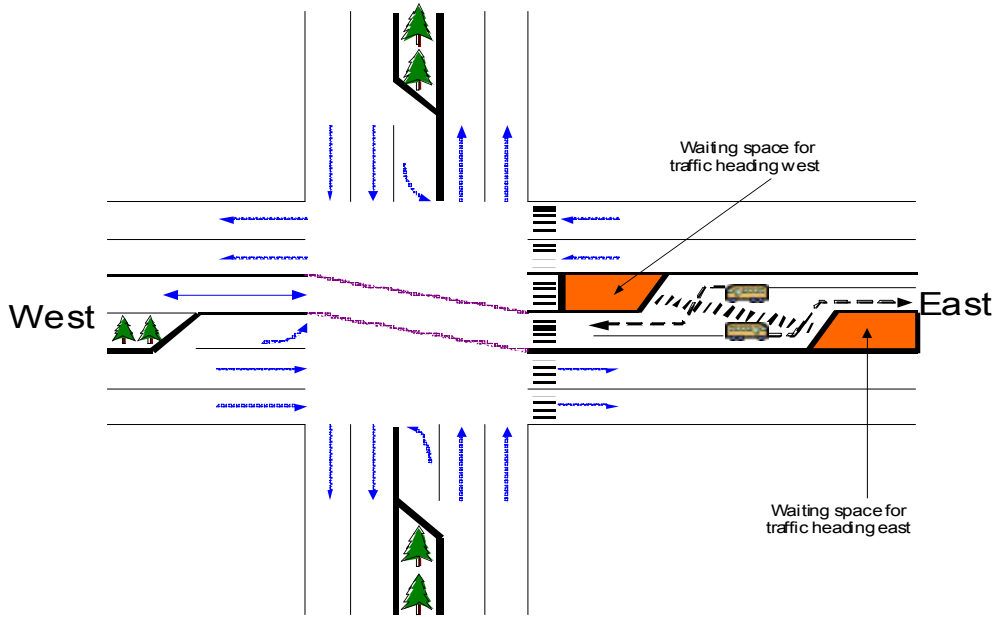
stop and crossing space of Configuration 7 is close to the adjacent intersection to the east, Configuration 7 can be extended easily in the east-west (horizontal) direction to become Configuration 5, with the passenger walkway connecting the two passenger waiting areas no longer required. To avoid passenger confusion about which of the two passenger platforms is the correct one for the intended trip, clear signage will be required.

The simple pattern observed earlier about the number of left-turn lanes sacrificed plus the number of passenger walkways required remains valid here.

Some of the configurations proposed so far will be used in [“Assessment of Feasibility for Implementation on Existing Corridors”](#) (page 25) as parts of the possible implementation of a proposed one-dedicated-lane system on the reference corridor. Another configuration will be introduced there that requires two dedicated lanes instead of one, but still saves one lane with respect to the current configuration.

## OPERATIONAL PERFORMANCE

For any segment of a one-dedicated-lane BRT, we use minimum headway  $h$  and travel time  $T$  as two measures of operational performance. For convenience of discussion and without loss of generality, we focus on a fixed route on which buses travel in the two opposing directions and from one end to the other, and are scheduled with a common and fixed headway throughout the entire day.



**Figure 12 Configuration 7: An integrated bus stop and crossing space implemented on one side of an intersection**

(Similar to Configuration 3, but with bus crossing) Bus stop and crossing space; one section and one entrance-exit; left-turning sacrificed for one side; doors on one side; long section

For the proposed system, these two measures are dependent. We assume that the crossing spaces are distributed along the route in such a way that the travel time  $t$  between any pair of two adjacent crossing spaces, including the time allocated for passenger boarding and alighting, is the same as that between any other such pair. Under this assumption, the minimum headway  $h$  of the bus service is twice this common travel time, to accommodate two-way traffic with only one dedicated lane. In other words,  $h = 2t$ .

With the number of crossing spaces between the two ends denoted as  $n$ ,  $T = t \times (n+1) = h(n+1)/2$ .  $T$  turns out to be a function of  $h$ ; this dependence is a unique characteristic of the proposed system. Note that the two measures are completely determined by  $n$  and  $t$ .

Given the dependence between  $T$  and  $h$ , not every pair of desired  $T$  and desired  $h$  can be achieved. In particular, given  $h$ ,  $t$  must be set to  $h/2$ , and there may not exist an integer  $n$  such that  $T = t \times (n+1) = h(n+1)/2$ . The design task is to determine a desirable pair of  $T$  and  $h$  such that

$$T = h(n+1)/2 \quad (1)$$

where  $n$  is a positive integer. Desirable values for  $T$  depend on the length  $L$  of the tour between the two ends, and a desirable  $T$  can be determined by dividing the length  $L$  by the target average travel speed  $v_0$ :

$$T = L/v_0, \quad (2)$$

where the average travel speed  $v_0$  incorporates the time spent on waiting for passenger boarding and alighting. Once the values of  $T$  and  $h$ , and hence those of  $t$  and  $n$ , have been determined, the average travel speed as defined by

$$v = L/T \quad (3)$$

can be used as an alternative performance measure in place of  $T$ .

The magnitude of target travel average speed  $v_0$  varies according to the demand and traffic conditions. In this paper, we focus on  $v_0 = 32.18$  kilometers (20 miles) per hour, which is close to the average travel speed of the VTA light rail system.

In the process, the number  $n$  of crossing spaces is also determined. Once  $h$  is determined,  $t$  is also determined. The remaining question is where these  $n$  crossing spaces should be located. The answer hinges upon the roadway configuration, customer demand, traffic condition, traffic control, and so on. To convey the unique features of the implementation, we deal with a closed system in which the bus enjoys complete transit signal priority, no surrounding traffic interferes with the bus movements, and passenger boarding and alighting requires an identical amount  $p$  of time at all stops. We further assume that the resulting  $n+1$  sections of the route divided by the  $n$  crossing locations have an identical length  $l$ .

Let us focus on a section between a given pair of adjacent crossing spaces, which we refer to as an intercrossing section. Denote the number of bus stops that are accommodated in an intercrossing section as  $m$ . Note that the number of bus stops that can be accommodated in this section is not unlimited: the more stops there are, the more time is needed for passenger operation and bus deceleration and acceleration; and less time remains for the bus to move from one crossing space to the other, so faster bus cruising speed is required. An upper bound must be imposed on bus cruising speed for safety. The relationship among the length  $l$  of an intercrossing section, the number  $m$  of bus stops on the section, the passenger boarding and alighting time  $p$  and the average bus driving (movement) speed  $\bar{v}$  of the bus is given as

$$\bar{v} = \frac{l}{t - (m+1)p} \quad (4)$$

Note that  $\bar{v}$  is an average speed, not the top bus cruising speed, and that the difference between this average speed and the top cruising speed increases with  $m$ . If the number of standalone bus stops  $m$  is allowed to vary with section and the distance between two adjacent crossing spaces is allowed to vary also, this relationship should be specified as

$$\bar{v}_s = \frac{l_s}{t - (m_s + 1)p} \quad (5)$$

However, it is important to achieve a constant travel time  $t$  for any intercrossing section so that the headway  $h=2t$  can be achieved.

To illustrate the relationships among average travel speed (or travel time), headway of bus operations, the distance between two neighboring crossing stations, and the number of crossing stations needed, refer to the simple and idealized time-space diagram of [Figure 4](#). As mentioned earlier, the average travel speed  $v$  is calculated as the distance  $L$  divided by the total amount of time  $T$  spent on moving and on waiting for passenger

boarding and alighting. Thus, the wait time is incorporated into average speed  $v$ . This is done also to simplify the space-time diagram, so that we can avoid horizontal line segments representing such waiting. We deal with the case where there are an odd number of crossing spaces on the route and express the odd number of crossing spaces  $n$  as  $2N-1$ ,  $N=1,2,\dots$ . In such a case, buses depart from the two ends at identical points in time with identical headway. For example, the first bus leaving End 1 and the first bus leaving End 2 both depart at time 0 so that they can cross at the crossing spaces. If the number of crossing spaces is an even number, the departure times of the buses leaving End 2 should differ from those leaving End 1 by  $t$  to enable crossing at the crossing spaces without delay.

The total time for a bus to travel from one end to the other is  $T = L/v = t \times (n+1) = h(n+1)/2$ . If we treat End 1 as the origin of the space coordinate, then the coordinates of locations of all crossing points are:  $Ln/(2N) = Ln/(2L/(vh)) = vhn/2$ , where  $n = 0, 1, 2, \dots, 2N-1$ .

If a standalone bus stop, that is, a bus stop that cannot accommodate a traffic crossing, exists between two adjacent crossing spaces, the time needed for the passenger operation, including passenger boarding and alighting, will contribute not just its entire time but twice that amount to the minimum headway of the bus service. The performance of this system when implemented can be improved by accommodating crossing at all bus stops that have sufficient space to accommodate both operations. Although this paper does not deal with the stochastic nature of demand and traffic, we note that the stochastic performance of the proposed system when actually implemented can be further improved by providing additional crossing spaces between two such adjacent integrated bus stops along the corridor.

The relationships derived above, for example, the relationship between the headway and the distance between two adjacent crossing stations, are useful in the planning stage to determine how many crossing spaces are needed and what the approximate distance between two adjacent crossing stations should be. Consider a one-dedicated-lane system with a length of  $L = 32.18$  kilometers (20 miles). Suppose that the target average travel speed is 32.18 kilometers (20 miles) per hour or 5.36 kilometers (3.33 miles) per 10 minutes. Also suppose a 10-minute headway. According to (1) and (2), the total travel time  $T$  is 60 minutes, and there should be  $n=11$  crossing spaces along the route, with the distance  $l$  between an adjacent pair being 2.67 kilometers (1.66 miles). (The actual average travel speed as calculated with (3) is the target travel average speed.) Suppose that two standalone bus stops divide the intercrossing section into three equally distanced segments and that 45 seconds is allocated for boarding and alighting for each stop. According to (4), the average bus driving speed is approximately 58.25 kilometers (36.2 miles) per hour, which is common in current practice.

## ASSESSMENT OF FEASIBILITY FOR IMPLEMENTATION ON EXISTING CORRIDORS

In this subsection, we first briefly describe the reference corridor. Any bus stop may be required to be a crossing space for some target headway as well. As a result, we address the worst-case situation and propose a geometric configuration to accommodate both a bus stop and a crossing space for each of the current light-rail stops under study. We then suggest locations for such integrated bus stop and crossing

space as a function of the average travel speed and minimum required headway. All the suggested one-dedicated-lane configurations or their variations were defined in the previous subsections. Finally, we point out the operational feasibility and the space saving of a one-lane BRT or light-rail system with respect to the current two-lane (that is, two-track) system.

As mentioned earlier, the reference corridor is the corridor served by the Blue Line of the VTA Light Rail of Santa Clara County of California (between the Alum Rock station and the Santa Teresa Station). We study in more detail the segment between Downtown San Jose and the Tasman Station in Milpitas because this segment is also traveled by the Green Line of the light-rail system and this overlap necessitates a shorter headway for this segment. [Appendix A](#) contains the route map of the VTA Light Rail System.

The southern portion of the Blue Line from the Children's Discovery Museum in downtown San Jose through Santa Teresa is separated completely from the rest of the traffic with dedicated right-of-way or elevated structures, without any at-grade interactions. The greatest portion is located in or over the median of a suburban-sprawl portion of State Highway 87. That portion is excluded from the scope of our study. The integrated nature of the combined highway and light-rail system makes the space requirement less serious.

We focus on the northern portion from the Alum Rock station through San James station, which is located in the downtown, and south of which the two-track route splits into two one-track routes through the heart of the downtown until they merge again near the Children's Discovery Museum. The portion spanning the heart of downtown is also excluded from this study because any downtown should be made public-transit oriented, and space saving should be a lower priority.

The study scope encompasses 21 stations. Two are located in a short stretch of elevated structure, which bypasses the busy intersection of Montague Expressway and Capital Avenue as well as entrances into the Great Mall of the Bay Area, a large and popular shopping mall. One stop has three tracks and two passenger platforms separating the three tracks. Since space seems to be no issue at these three stops, they are excluded from this study.

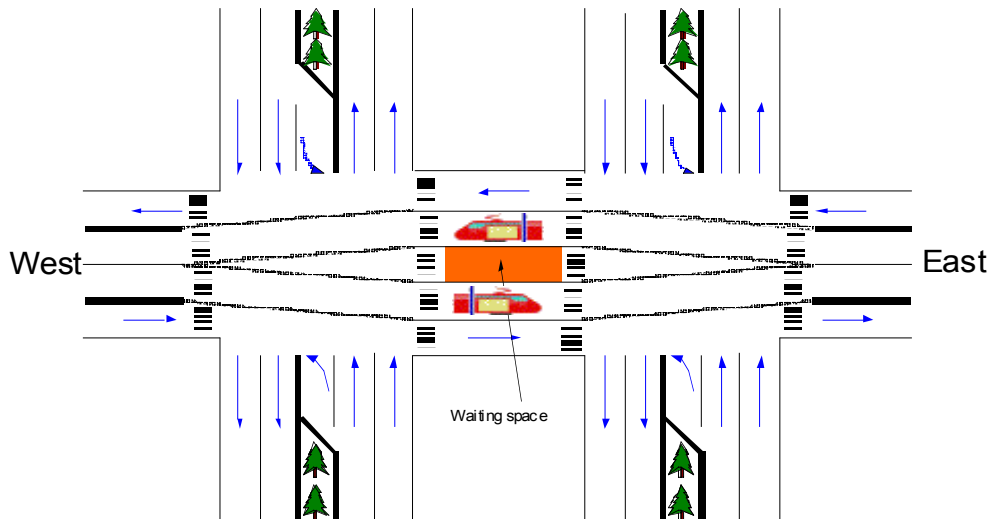
For each of the remaining 18 stops, we will show the feasibility of providing an integrated bus stop and crossing space, instead of a standalone bus stop or a standalone crossing space. Only two of these stops are not equipped with a left-turn lane for both directions. Both are located in a busy downtown area, adjacent to each other. One, the Japan Town and Ayer Station, is located in a particularly narrow section of the corridor, with only one regular (through-traffic) lane for each of the two directions and without any parking or other space. One passenger platform is located in between the two light-rail tracks, and the station spans one entire section between two intersections.

The length of the section is suitable for having one entrance-exit at each of the two intersections. This current configuration is depicted in [Figure 13](#). A simple variation of Configuration 5 can be used as a corresponding integrated bus stop and crossing space for the current configuration if a one-dedicated-lane system is to be implemented on this portion of the Blue Line. The variation is identical to Configuration 5, with the following exceptions:



- There should be only one regular lane for each of the two traffic directions instead of the two regular lanes shown in Configuration 5.
- The left-turn lane shown in the section to the west of the bus stop-crossing space on Configuration 5 should be absent because there is no such left-turn lane in the current configuration.

Note that this variation requires one less lane than the current configuration.



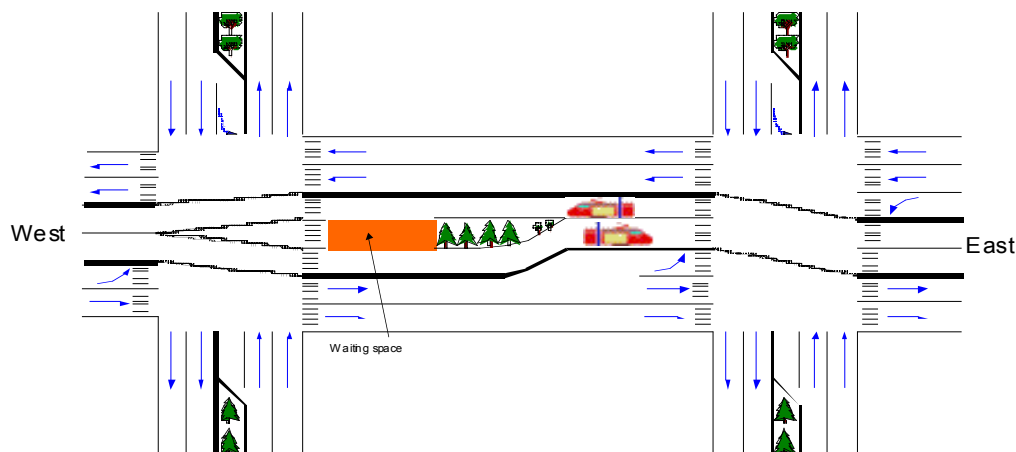
**Figure 13 Current configuration of a station with one platform, one regular lane in each direction**

Stop and no need for crossing; one section and two entrances-exits; no left-turning; doors on both sides; long section

The other station, Mission and Civic Center, is similar except that there are two regular (through-traffic) lanes in each of the two directions, and the section is too long to have one entrance-exit on each side of the section. This configuration is depicted in [Figure 14](#). A variation of Configuration 7 can be used in this situation as a corresponding integrated bus stop and crossing space for the current configuration if a one-dedicated-lane system is implemented on this portion of the Blue Line. In the section west of the integrated bus stop and crossing space of the variation, there should be only one regular lane in the west-to-east direction and there should be no trees. Configuration 7 requires one less lane than the current configuration.

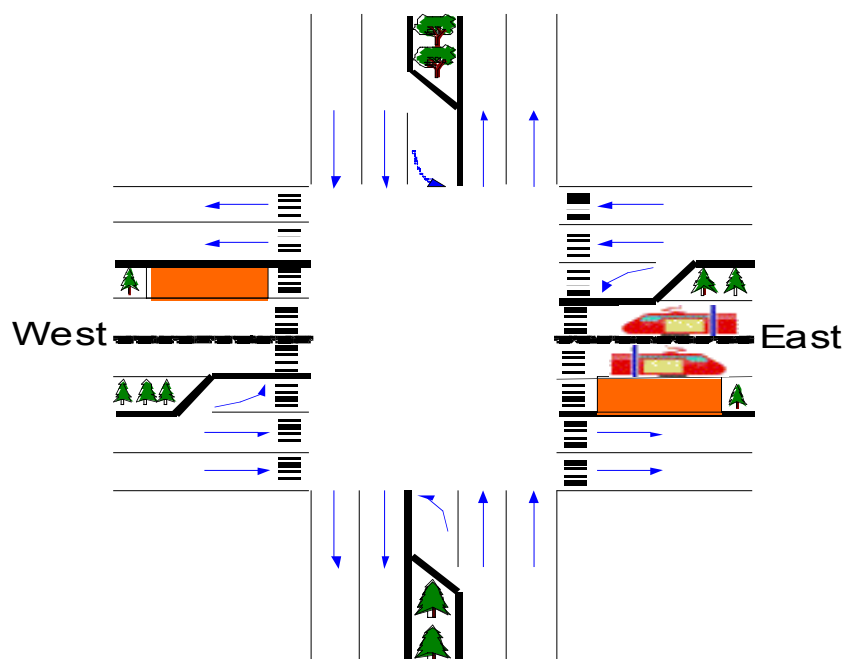
Note that in [Figure 13](#) and [Figure 14](#), the configurations are equipped with one platform (in between two tracks) serving passengers in both directions, and the corresponding sections are wider than at least one of their neighboring sections. This is because the additional space is needed for passenger access, boarding, and alighting in the presence of a space shortage.

Each of the remaining 16 current stations has a left-turn lane at the intersection(s) involved. Of these, eleven are equipped with two passenger platforms, one for each of the two traffic directions, and are configured in such a way that the two platforms are separated by an intersection, as illustrated in [Figure 15](#). The width of the right-of-way,



**Figure 14 Current configuration of a station with one platform and one entrance-exit, but without a left-turn lane at the entrance-exit**

Stop and no need for crossing; one section and one entrance-exit; no left-turning at the entrance-exit; doors on both sides; long section



**Figure 15 Configuration of a station with two platforms separated by an intersection and one entrance-exit on each side of intersection**

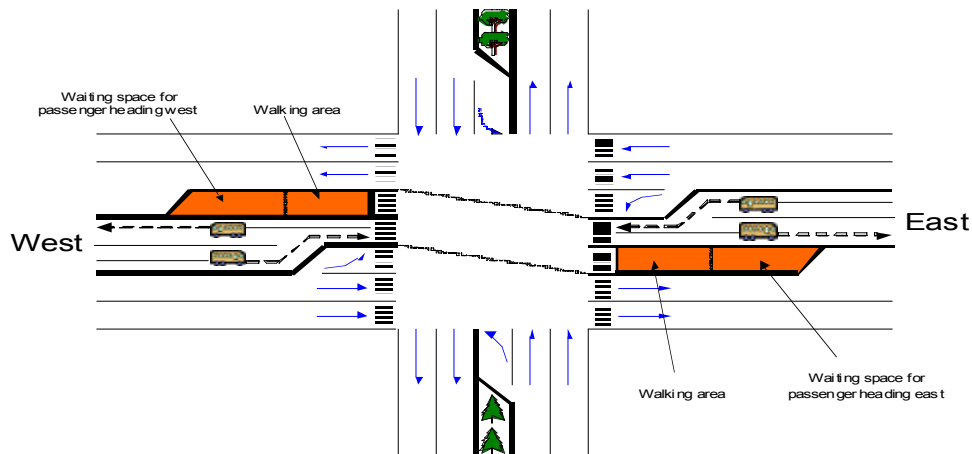
Stop and no need for crossing; two sections and two entrances-exits; left-turning; doors on both sides; short or long section

with possible parking or bike-lane space discounted, is eight lanes, which is constant along the sections associated with the 11 stations.

Configuration 6, shown in [Figure 11](#), can be used as a corresponding integrated bus stop and crossing space for the current configuration if a one-lane system is implemented on



this portion of the Blue Line. Note that Configuration 6 requires two fewer lanes than the current configuration. Configuration 8.a, shown in [Figure 16](#), can also be used as a corresponding integrated bus stop and crossing space for the current configuration if a one-lane system is implemented on this portion of the Blue Line.



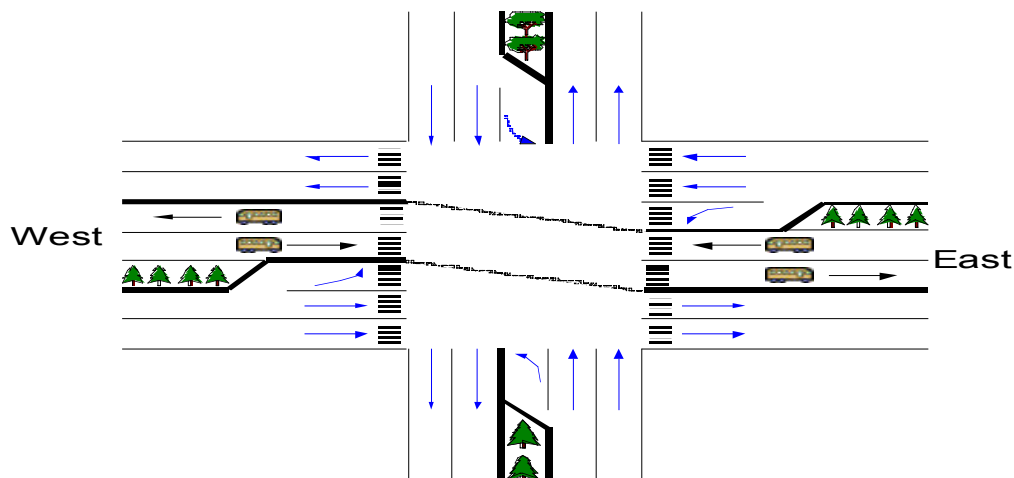
**Figure 16 Configuration 8.a: An integrated bus stop and crossing space implemented on two sides of an intersection**

Stop and crossing; two sections and two entrances-exits; left-turning; doors on one side; long or short section

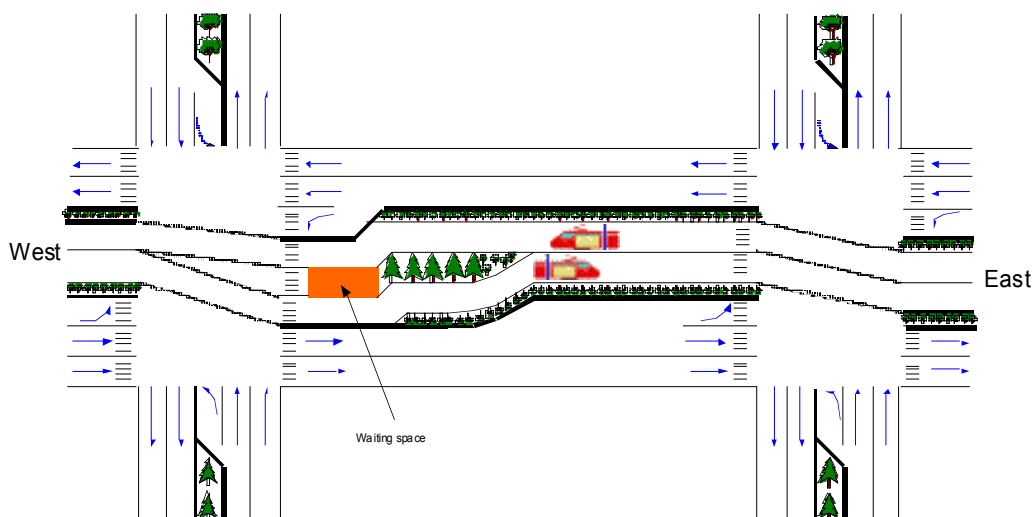
Configuration 8.a requires one less lane than the current configuration. A main difference between Configurations 6 and 8.a is that the latter provides a left-turn lane at the intersection for both directions, at the expense of dedicating a right-of-way the width of one traffic lane for the passenger operation. Also, Configuration 8.a dedicates two lanes for the bus system. It requires three lanes for a portion of an integrated bus stop and crossing space, and the entire system has two dedicated bus lanes except at the intersection where an integrated bus stop and crossing space is located. The resulting interruption to the two-way traffic should be minimum, yet the system requires one less lane than the current configuration. Configuration 8.b, shown in [Figure 17](#), illustrates the dedication of two lanes to the bus operation in any section without a bus stop or a crossing space.

The other five of the sixteen stops are configured with one platform in between the two tracks serving passengers for both directions, as depicted in [Figure 18](#). Configuration 7 can be used as a corresponding integrated bus stop and crossing space for the current configuration if a one-dedicated-lane system is to be implemented on this portion of the Blue Line. Configuration 7 requires two fewer lanes than the current configuration, although the left-turn lane at the intersection for westbound traffic is sacrificed.

Like the configurations depicted in [Figure 13](#) and [Figure 14](#), the configuration illustrated in [Figure 18](#) is equipped with one platform (in between two tracks) serving passengers of both directions. Depending on space availability, its neighboring sections may or may not be narrower. The two tracks typically are brought back next to each other in the sections adjacent to a stop, with only safety spacing between the two tracks and no additional space between them. If a neighboring section is of equal width and no additional regular



**Figure 17 Configuration 8.b: Dedication of two lanes to the bus operation in any section without a bus stop or a crossing space**



**Figure 18 Configuration of current station with (a) one shared platform and (b) one entrance-exit**

Stop and no need for crossing; one section and one entrance-exit; left-turning; doors on both sides; short or long section

lanes are provided for the section, the unused space can be a safety buffer between the light-rail tracks and the regular lanes and those used for aesthetics. Figure 18 depicts such a case.

For the purpose of testing the operational performance of the proposed one-dedicated-lane system in a high-demand situation, we study the minimum headway  $h$  and travel time  $T$  by focusing on the segment of the Blue Line between the Tasman station and the San James station. This segment was chosen because it is shared by the Blue Line and the Green Line, and the demand for bus crossing will be much higher than

in any other portion of the VTA light-rail system. Assuming that all crossing spaces are collocated with a bus stop, [Table 1](#) summarizes the result.

**Table 1 Locations of Crossing Spaces and Average Bus Driving Speeds for 7.5-minute Headway**

(Travel Time Between Two Adjacent Crossing Spaces = 3.75 minutes)

<b>Current Stops with Hypothetical Crossing Spaces in Bold Italic</b>	<b>Distance Between This and Next Current Stop</b>	<b>Average Driving Speed between This and Next Crossing Spaces (<math>\bar{v}</math>)</b>
<b><i>Tasman</i></b>	932 m (3059 ft)	49.1 km/h (30.5 m/h)
River Oaks	909 m (2982 ft)	
<b><i>Orchard</i></b>	889 m (2919 ft)	41.8 km/h (26.0 m/h)
Bonaventura	677 m (2223 ft)	
<b><i>Component</i></b>	945 m (3100 ft)	45.7 km/h (28.4 m/h)
Karina	768 m (2521.5)	
<b><i>Metro</i></b>	1001 m (3285 ft)	62.8 km/h (39.0 m/h)
Gish	1359 m (4458 ft)	
<b><i>Mission / Civic Center</i></b>	789 m (2588 ft)	41.8 km/h (26.0 m/h)
Japan Town / Ayer	776 m (2546 ft)	
St. James	N/A	N/A

Each of the two light-rail lines has a 15-minute headway; therefore, we assume a 7.5-minute headway for the 9.01-km (5.6-mile) segment. The travel time  $t$  between any two adjacent crossing spaces has to be 3.75 minutes. At every other current stop, a crossing space is provided. Therefore, the number of crossing spaces  $n$  is 4, and the number of standalone bus stops between two adjacent crossing spaces is  $m = 1$ . The resulting travel time for this entire segment is  $5 \times 3.75 = 18.75$  seconds, which is a little less than the corresponding travel time of the current light-rail system. This result is encouraging. We have attempted to retrofit part of an existing system, which was designed without regard to the performance characteristics of the proposed system, and expect that a newly built one-dedicated-lane system would produce better results. Time allocated for passenger boarding and alighting is 45 seconds for each stop, as assumed in [Operational Performance](#), [page 22](#). As a result, Equation (5) provides the average bus driving speeds for the five intercrossing sections (delimited by the crossing spaces), none of which exceeds 64.36 kilometers (40 miles) per hour or falls under 40.23 kilometers (25 miles) per hour.

Ideally, all the crossing spaces are equally distanced, the traffic conditions along all intercrossing sections delimited by these crossing spaces are identical, and the demand is uniform across all stops, so that the time required to travel any intercrossing section is constant. (We ignore the surrounding traffic and hence the need for coordination with traffic signals, because we focus on a closed system in this paper.) However, this cannot be achieved by any existing systems nor any real-world systems yet to be planned and built. However, the most important thing is the constant travel time between two neighboring crossing spaces. To approach the ideal for this particular existing corridor, we rely on adjusting the average speed of bus travel according to Equation (4), but impose a limitation on the fastest possible speed for safety and comfort. These fastest possible speeds are also shown in [Table 1](#).

Based on this study, we believe that the proposed one-dedicated-lane system is feasible for a commuter corridor like the one we just studied. As a result, the proposed system can save at least one lane's worth of right-of-way.

## **SUMMARY**

We have proposed the concept of a one-dedicated-lane BRT or light-rail system, which should be applicable to both developed and developing countries. We provided conceptual designs and geometric-configuration sketches for the bus stop and crossing space, considering the three different cases where the bus stop and crossing space may be located separately or jointly. Based on a time-space diagram, we studied the deterministic relationships among the bus travel speed, headway of bus operations, distance between two neighboring crossing stations, and number of crossing stations needed for the entire system. We applied the results to a reference corridor that is currently served by the Valley Transportation Authority (VTA) Light Rail of Santa Clara County, California, between the Alum Rock station and Downtown San Jose on the Blue Line.

The research shows that the proposed geometric configurations could support two-way traffic with only one dedicated lane and have the potential to achieve good operation performance. For corridors not having an existing BRT or light-rail service implemented on the median and not having sufficient right-of-way to implement a two-dedicated-lane system, the proposed system provides hope for implementing a BRT system. For busy commuter corridors that have sufficient right-of-way but do not have sufficient demand to warrant dedicating two mixed-use lanes to public transportation, the proposed system is particularly useful as an intermediate step toward a two-dedicated-lane system because of its potential for facilitating transit-oriented development.

More work is being conducted to provide details about the geometric designs of the bus stops and crossing spaces, considering more practical operations issues. The actual performance of the proposed system will be stochastic, depending on the demand patterns, traffic conditions, and system disturbances. Advanced technologies such as bus signal priority and advanced vehicle control may be useful for maximizing the performance. Control of the bus speed profile requires technologies that monitor the current position, current speed, and schedule of a bus; communicate the information to a system control system; compute the required speed profile adjustment; and convey the resulting instructions to the driver and the onboard bus control system, if there is one. A computer-simulation model should be developed to analyze the system performance under more complex and practical circumstances. The practicality of the proposed system in terms of operator acceptance and user acceptance should be verified by consultation with expert practitioners and transit users through further study.

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## **SPACE MINIMIZATION FOR IMPLEMENTING DEDICATED BUS RAPID TRANSIT/LIGHT-RAIL SYSTEM**

### **And Expanding a One-Dedicated-Lane System to Two Lanes**

This section is divided into the following subsections:

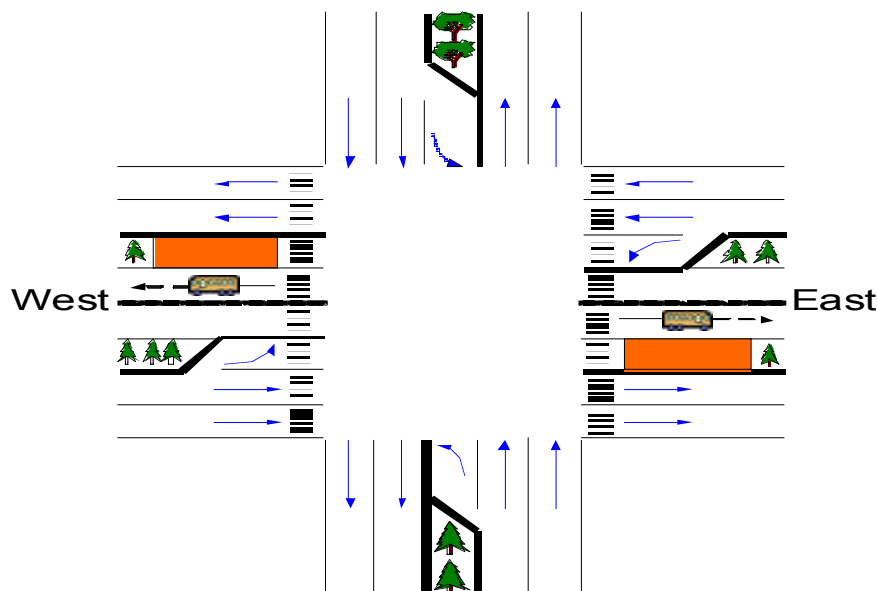
- [“Problem Definition—The Prevailing Configuration of a Bus Stop in a Two-Dedicated-Lane System”](#) defines the problem addressed in this section: the prevailing geometric configuration of a bus stop for a two-dedicated-lane BRT or light-rail system, and the dedication of a space equivalent to four traffic lanes.
- [“Bus Stop Implementations Requiring Only a Space of Three Lanes”](#) proposes several configurations requiring a space equivalent to only three lanes at a bus stop, based on two key ideas proposed for a one-dedicated-lane system.
- [“Expanding One-Dedicated-Lane Systems to Two Lanes”](#) first discusses the main ideas behind the one-dedicated-lane systems. It then addresses ways to expand the previously proposed one-dedicated-lane systems to two-dedicated-lane systems, as the demand for public transportation grows and dedication of an additional lane is accepted by the general public.
- [“Summary”](#) summarizes the discussion in this section.

#### **PROBLEM DEFINITION—THE PREVAILING CONFIGURATION OF A BUS STOP IN A TWO-DEDICATED-LANE SYSTEM**

The proposed concept works for both BRT systems and light-rail systems. In this discussion, we address only BRT explicitly, but the same information applies to light-rail systems unless an exclusion is pointed out.

Bus rapid transit (BRT) systems can be implemented with or without dedicated lanes. Dedicating two lanes, one for each direction, for BRT systems can isolate bus traffic from the surrounding traffic and can take advantage of transit signal priority, resulting in significantly shorter and more reliable travel time. However, space availability and the will of the driving public may hinder its implementation. One serious issue is the space required for a bus stop along an arterial serving a busy commuter corridor. The width of such a corridor typically remains constant throughout the corridor or changes only occasionally. The traffic capacity of an arterial equipped with a dedicated BRT system tends to be limited by the capacity at such a bus stop. Therefore, the width requirement for a bus stop on a dedicated BRT system should be minimized as much as possible. Often, such minimization is not only an issue of space optimization but also a feasibility issue. Many busy commuter corridors have a width equivalent to seven traffic lanes. If a bus stop occupies four lanes, it is impossible to accommodate two lanes of regular traffic in each direction. This can cause significant traffic problem for nonbus traffic.

Several designs for such a bus stop exist. [Figure 19](#) is perhaps the prevailing design. We refer to this configuration as Configuration F, where “F” signifies the four-lane requirement for the bus stop.



**Figure 19 Configuration F: One passenger platform and entrance-exit on each side of intersection, and one left-turn lane for each direction**

This configuration allows two lanes of regular traffic per direction, but eight lanes are required to accommodate this bus stop. In the next subsection, we propose three configurations that require a width of only three traffic lanes.

This and all configurations proposed later illustrate the proposed operational concept. For ease of comparison, the traffic in each sketch moves along the east-west direction, that is, horizontally between the left- and right-hand sides of the diagram. Two lanes are provided for through traffic for each of the two directions. The width of right-of-way is measured in the unit of a traffic lane, regardless of whether the lane is a through lane for regular traffic, a left-turn lane, a dedicated bus lane, or a parking lane. A passenger platform is treated as being as wide as a traffic lane, whether it is dedicated for use only by passengers heading in one direction or is shared between passengers heading in both directions. We ignore possible curbside parking altogether in the diagrams.

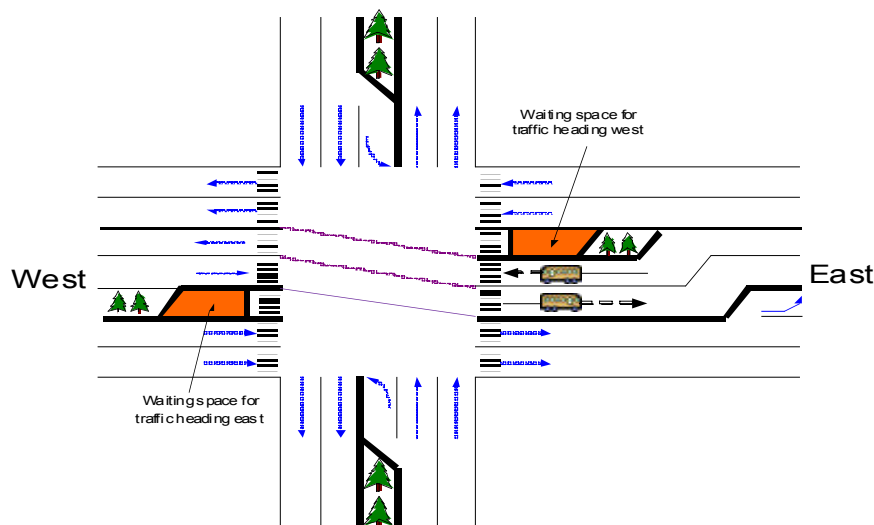
As in [Figure 19](#), major design features will be specified in the figure caption for the following sketches. Such sketches must be expanded into detailed geometric designs in the future according to related standards. Detailed standards for designing bus stops and other roadway features can be found in the existing literature.

## **BUS STOP IMPLEMENTATIONS REQUIRING ONLY A SPACE OF THREE LANES**

In this subsection, we propose four configurations for accommodating a bus stop of a dedicated BRT system and their variations. We describe in detail the first one, as improvements to the configuration in [Figure 19](#), and briefly discuss the next two. Each of these first three involves two physically separated passenger platforms, one for each direction; the fourth uses a shared platform for passengers of both directions.

[Figure 20](#) summarizes the design of a bus stop that requires three lanes. We refer to this as Configuration T-1; “T” signifies the three-lane width requirement. This configuration

can be implemented on an arterial equipped with a right-of-way whose width is equivalent to seven traffic lanes, leaving four lanes for the regular traffic



**Figure 20 Configuration T-1: One passenger platform and entrance-exit on each side of intersection, and no left-turn lane for both directions**

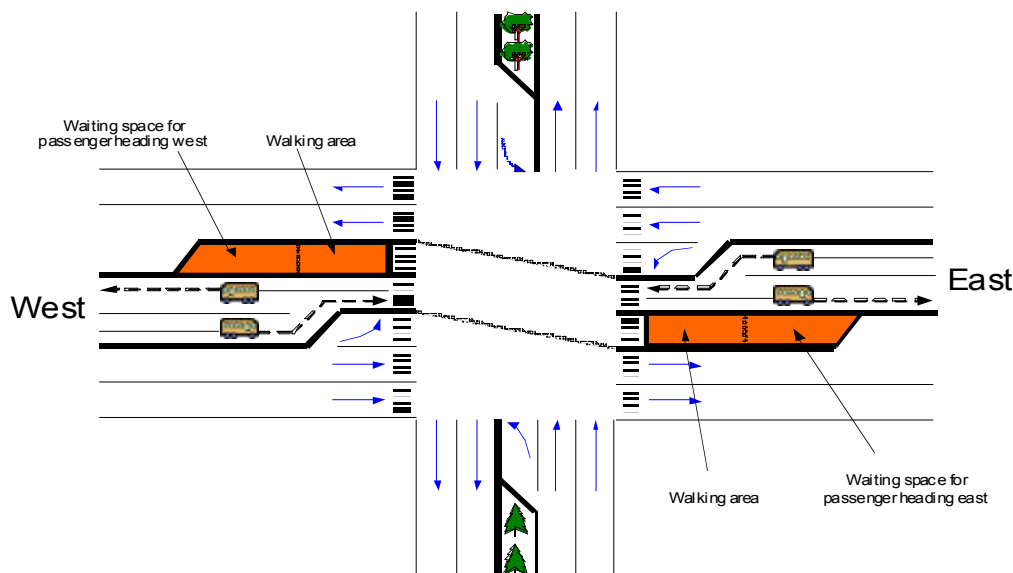
Configuration T-1 incorporates four modifications to Configuration F. (Because it is symmetrical, we address only the westbound lanes; corresponding modifications are needed for the eastbound lanes.)

1. There is no left-turn lane. This is a requirement only for locations with a bus stop, as will be explained in the text for [Figure 21](#).
2. The passenger platform for the westbound direction from west of the intersection to the space vacated by the left-turn lane for the westbound traffic has been moved.
3. The space for the BRT is realigned so that three lanes along the median are dedicated to the BRT.
4. The bus lanes on the two sections with lane delimiters (which are slanted with respect to the direction of the arterial) are connected.

In Configuration T-1, the east-west left-turn lanes at the intersection are sacrificed to make space for the two passenger platforms. Where this is not appropriate, the two left-turn lanes can be retained, but only a single traffic lane is dedicated to the system at the intersection, as shown in [Figure 21](#). We refer to this Configuration T-1-a, where the suffix “a” signifies an alternative. This configuration differs from Configuration T-1 in two more ways:

1. The passenger platform in this configuration is on the opposite side of the arterial.
2. The passenger platform is longer, because space is needed away from the single dedicated lane for a bus to stop to avoid blocking the single dedicated lane for the traffic of the opposite direction.





**Figure 21 Configuration T-1a: An integrated bus stop and crossing space implemented on two sides of an intersection**

Two sections and two entrances-exits; left-turning; doors on one side; long or short section

Although only one lane is dedicated to BRT at this intersection, the crossing of buses traveling in opposite directions poses no problem: buses will not stop on this single dedicated lane but only at locations where they will not block the bus traffic for the opposite direction. That is, buses will stop only next to the half of a passenger platform that is away from the intersection, as shown in [Figure 21](#). If two buses traveling in opposite directions need to cross each other at this intersection, minimum coordination is needed. The buses can cross in the middle of the intersection, or one bus can yield to the other by waiting for the other to clear the intersection and the single dedicated lane.

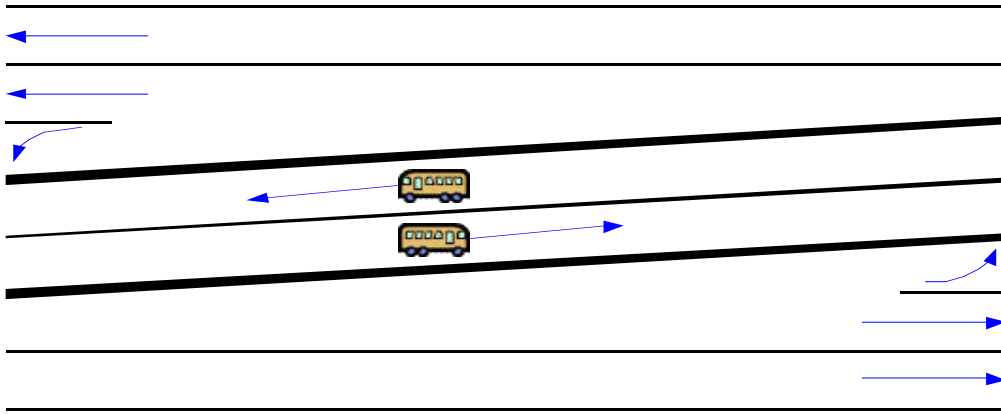
The crossing issue addressed for one-dedicated-lane systems is more limiting and difficult because buses traveling in opposite directions can only cross each other at designated crossing spaces. The crossing involved in Configuration T-1.a is an issue only for a few spots along the arterial.

The configuration for a section with no bus stop is illustrated in [Figure 22](#). Two lanes are dedicated to bus traffic, one for each direction; left-turning is provided for both directions; the two dedicated lanes are slanted to use the otherwise unused or underused space between the two left-turn lanes located on the two ends of the section; two regular lanes are available for each direction; and all these functions are accommodated on a seven-lane arterial. The configuration for any intersection involving no bus stop is illustrated in [Figure 23](#). Note the slanting of the bus lanes at the intersection.

In Configuration T-1 ([Figure 20](#)), left-turning on the east end of the section on the east, like left-turning on the west end of the section on the west, is accommodated.

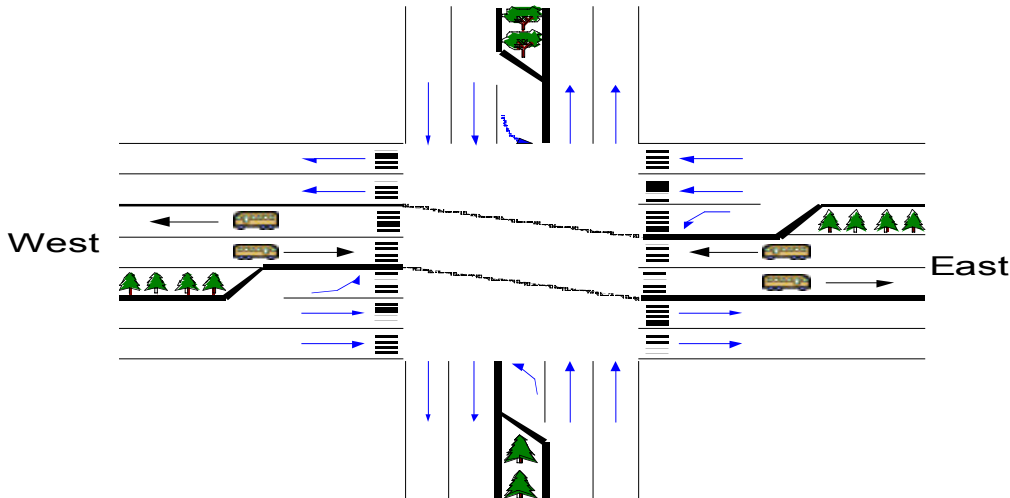
Two defining features of Configuration T-1 are the use of the space of a left turn for a passenger platform instead, and slanting the bus lanes with respect to the direction of the arterial, including the lanes within a section ([Figure 21](#) and [Figure 22](#)) and those





**Figure 22 A section involving no bus stop**

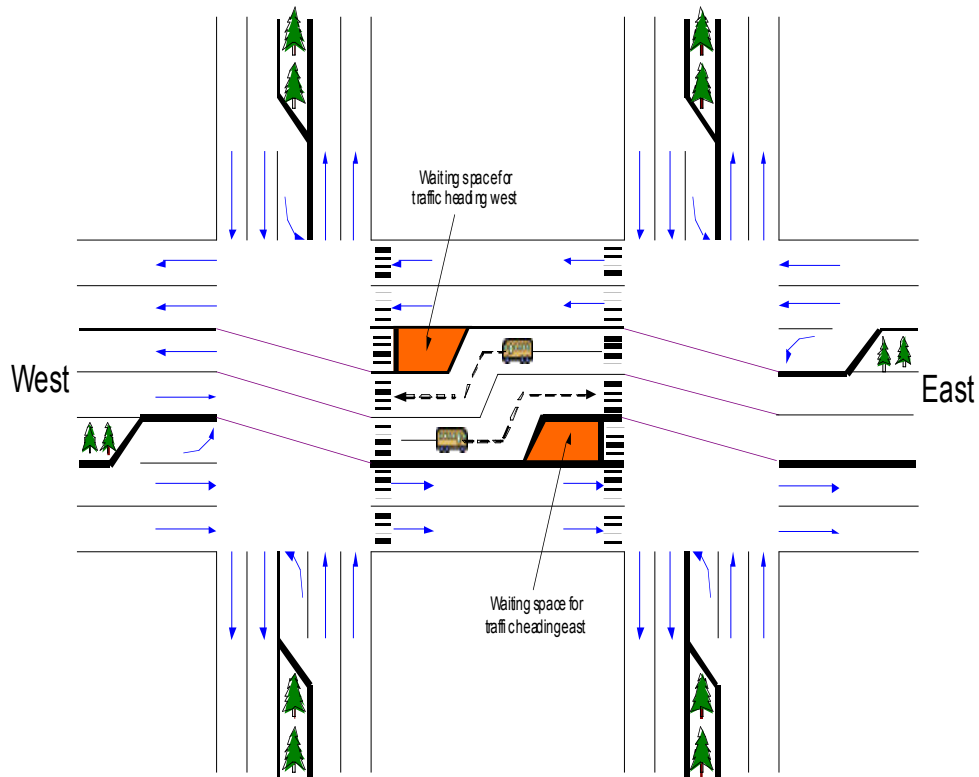
Two dedicated bus lanes, with slanting; left-turning provided for both directions; two regular lanes for each direction; all accommodated on a seven-lane arterial.



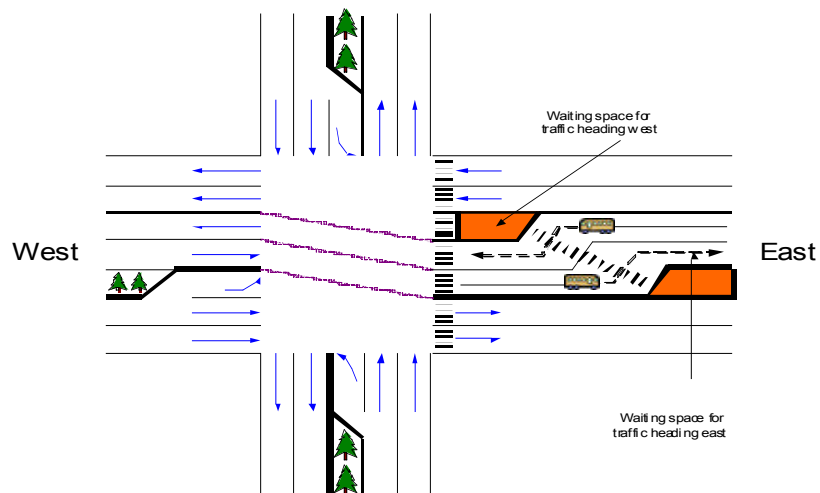
**Figure 23 Configuration for intersection with no bus stop, with slanted bus lanes**

crossing an intersection ([Figure 20](#)). In the previous section, they were proposed to enable a one-dedicated-lane BRT or light-rail system.

Similarly, we can have the following two configurations: Configuration T-2, as illustrated in [Figure 24](#), and Configuration T-3, as illustrated in [Figure 25](#). Each requires a width equivalent to only three traffic lanes and can be accommodated on an arterial equipped with a right-of-way width equivalent to seven traffic lanes. In Configuration T-2, left-turning is sacrificed on both ends of the section, but in Configuration T-3, left-turning is sacrificed on only the west end of the section. This is a good choice particularly when left-turning for the east end of the section is crucial or the section is too long to locate the two passenger platforms on the two ends.

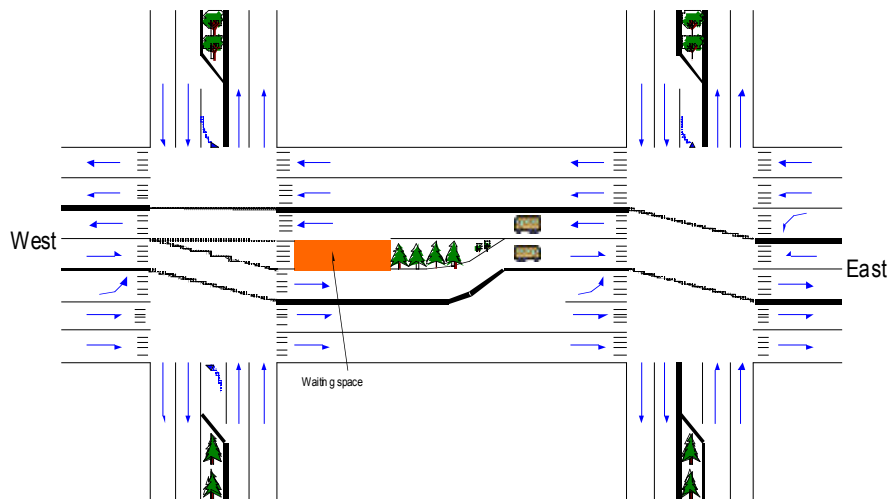


**Figure 24 Configuration T-2: One passenger platform and entrance-exit on each side of the section and no left-turn lanes in the section**



**Figure 25 Configuration T-3: Two passenger platforms connected by a passenger walkway, only one entrance-exit, and left-turning sacrificed only on the west end of the section**

Configurations T-1, T-2, and T-3, or variations, each have two physically separated passenger platforms. We now propose Configuration T-4 (Figure 26) in which passengers traveling in either direction share a common platform in the middle of the median. In Configuration T-4, we assume that the width required for such a shared platform is the same as, or not significantly larger than, the width required for a platform serving passengers traveling in only one direction. This shared platform saves space, eliminating the need to sacrifice one left-turn lane at the intersection, so only one left-turn lane is eliminated.



**Figure 26 Configuration T-4: One shared passenger platform, with only one entrance-exit, and only one left-turn lane sacrificed**

## EXPANDING ONE-DEDICATED-LANE SYSTEMS TO TWO LANES

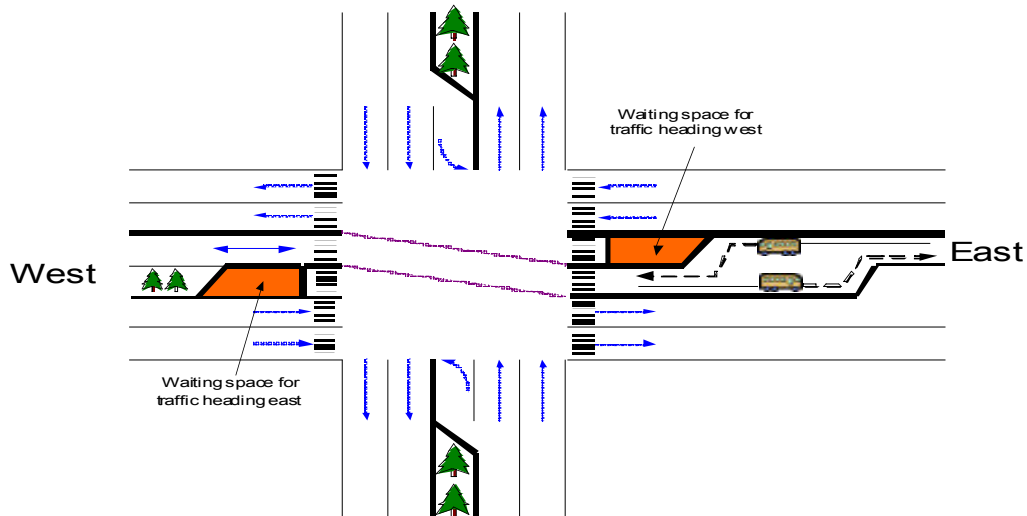
Designing a one-dedicated-lane BRT system involves several critical new issues:

- how to accommodate crossing of buses traveling in opposite directions, which requires one additional lane beyond the one dedicated lane, without any negative impact on the traffic using the regular, mixed-flow lanes
- how to accommodate passenger access, boarding, and alighting with a minimum amount of space
- whether such accommodation can be provided at enough locations at regular distance intervals so as to provide the same or similar level of service that is achievable by the conventional counterparts

The basic idea behind the proposed concept is simple. Bus crossing is accommodated on the otherwise unused or underused median space resulting from provision of the left-turn lanes. Although not necessary, bus stops can replace some left-turn lanes. Crossing spaces can be placed strategically to achieve the desired bus headway and travel time. As in the case of a two-dedicated-lane BRT system, bus speed profiles can be adjusted and transit signal priority employed to maximize adherence to the schedule.

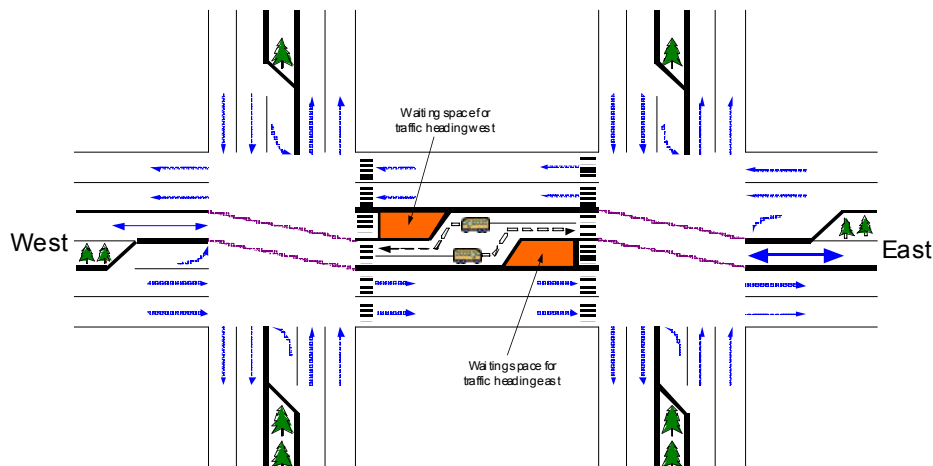
In the previous section, we discussed design options for the three functions, organized them into five dimensions, and proposed configurations for standalone crossing spaces,

standalone bus stops, and integrated facilities accommodating both a crossing space and a bus stop. Integrated facilities are the most challenging function to design for. The three configurations shown in Figure 27, Figure 28, and Figure 29, are identical to Figure 11, Figure 10, and Figure 12, respectively, and are repeated here for reading convenience.



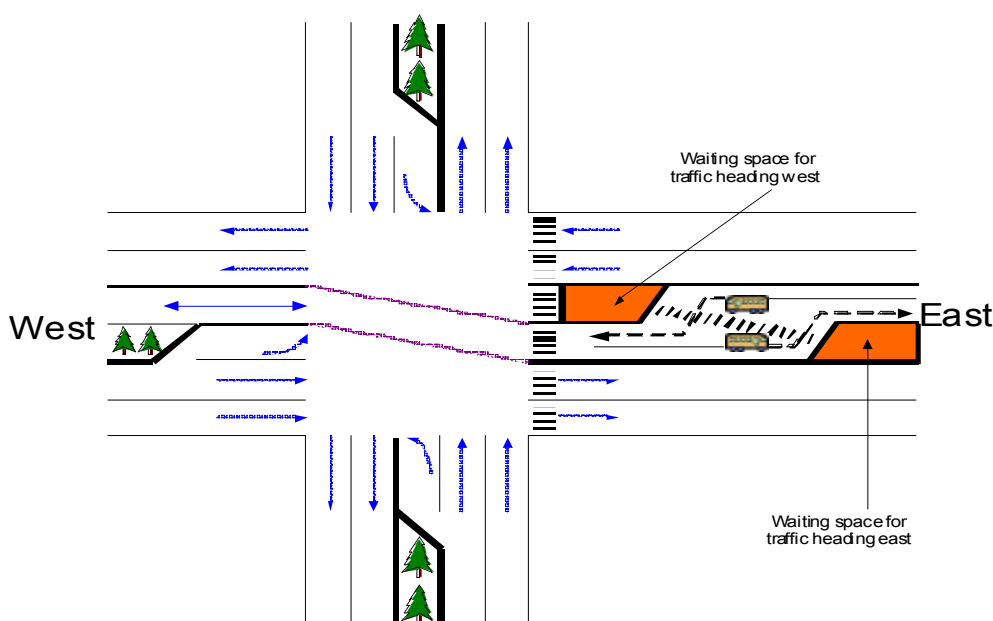
**Figure 27 The one-dedicated-lane BRT corresponding to Configuration T-1: An integrated bus stop and crossing space located on two sides of an intersection**

Bus stop and crossing space; two sections and two entrances-exits; left-turning sacrificed; doors on one side; long or short section



**Figure 28 The one-dedicated-lane BRT corresponding to Configuration T-2: An integrated bus stop and crossing space implemented on one section**

Bus stop and crossing; one section and two entrances-exits; left-turning sacrificed on both ends; doors on one side; long section



**Figure 29 The one-dedicated-lane BRT corresponding to Configuration T-3: An integrated bus stop and crossing space implemented on one side of an intersection**

Bus stop and crossing space; one section and one entrance-exit; left-turning sacrificed for one side; doors on one side; long section

They are identical to Configurations T-1, T-2 and T-3, except that they have one less dedicated lane and have extra space allocated for buses traveling in the opposite directions to cross.

Expansion of the three one-dedicated-lane systems to two lanes is straightforward, as long as the extra space of one additional lane is available. For each of the three expansions, all that is needed is to add the additional lane immediately next to the one lane already dedicated in the corresponding one-dedicated-lane system. Because the crossing space is no longer needed, any such space dedicated in any of the one-dedicated-lane systems can be freed up for other uses.

Some of the one-dedicated-lane systems can be expanded to different two-dedicated-lane systems. For example, the one-dedicated-lane system illustrated in [Figure 29](#) can be expanded to become either Configuration T-3 ([Figure 25](#)) or Configuration T-4 ([Figure 26](#)).

## SUMMARY

In typical existing or planned BRT or light-rail systems implemented with two dedicated traffic lanes, a space equivalent to four traffic lanes is dedicated for a bus stop. Since locations at or near these stops tend to be traffic bottlenecks for the traffic traveling on regular traffic lanes, minimizing the width requirement for these stops is critical. In this paper, we proposed four implementations requiring only three lanes at a bus stop, based

on two key ideas proposed for a one-dedicated-lane system. The proposed configurations or their variations require eliminating two, one, or no left-turn lanes. Although the different reductions of sacrificed left-turn lanes from two come with different forms and degrees of complexity, the different configurations provide a rich set of implementation choices.

We also proposed geometric configurations that expand the previously proposed one-dedicated-lane systems to their corresponding two-dedicated-lane systems. The expansions are straightforward, and some of the one-dedicated-lane systems can be expanded to different two-dedicated-lane systems.

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## CONCLUSIONS

This section is organized as follows:

- “[Future Research](#)” summarizes several important topics for future research
- “[Summary](#)” provides concluding remarks

### FUTURE RESEARCH

The scope of this project is limited to identifying and resolving major implementation issues, and assessing the practicality and performance of the proposed one-dedicated-lane BRT systems or light-rail systems. We believe that this project has demonstrated the practicality of the proposed systems.

A key issue is the crossing of buses traveling in opposite directions, and such crossing requires space and may entail delays. Although a deterministic study demonstrates good performance, one important issue must be studied before we can recommend a full-scale development effort for real-world deployment. The performance study of this project focuses on a closed system, ignoring the surrounding traffic and the stochastic nature of demand patterns. An important topic for future research is to develop detailed operating rules, including speed profiles and transit signal priority, to accommodate the stochastic impact of surrounding traffic and passenger demand, and to use computer simulation to select the best rules. We address this issue in more detail below.

The proposed system requires that a minimum set of crossing spaces be strategically placed so that the travel time  $T$  between any adjacent pair of such spaces is the same as that between any other such pair. Consequently, the minimum headway  $h$  is equal to twice the constant travel time  $T$ , that is,  $h = 2T$ . Any delay of a bus reaching a crossing space will cause a delay to both the schedule of buses traveling in its direction and the schedule of buses traveling in the opposite direction.

A key issue is to ensure on-time crossing, particularly to recover from the delay of a bus. A further research project should seek to develop detailed operating rules, including speed-profile control and transit signal priority (TSP), to ensure on-time crossing, and to use computer simulation to study and compare the stochastic performance of the rules. Control of bus speed profile also requires technologies that monitor the current position, current speed, and schedule of a bus; communicate the information to a system control system; compute the required speed profile adjustment; and convey the resulting instructions to the driver and the on-board bus control system, if so equipped.

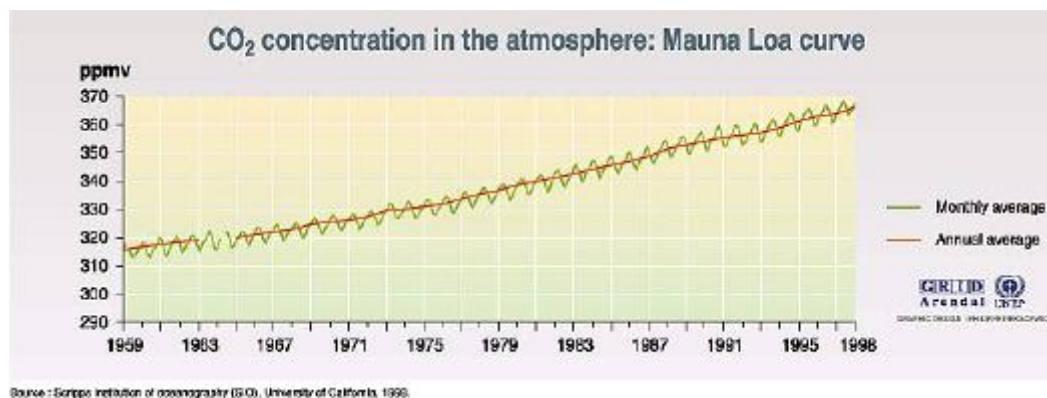
We briefly discuss the importance of this future research topic, in both the context of the feasibility study of the proposed one-dedicated-lane BRT or light-rail systems and the context of combating the problem of excessive emission of greenhouse gases. More research is needed to minimize possible safety hazards of the proposed one-dedicated-lane system. For example, signals should be installed and coordinated along the entire route to indicate dynamically the allowed traffic direction—green for one direction always accompanied by red for the opposite direction.

A research proposal about this important future research topic entitled *Developing Operating Rules and Simulating Performance for One-Dedicated-Lane Bus Rapid*

*Transit/Light Rail Systems* has been submitted to California Partners for Advanced Transit and Highways (PATH), in response to PATH Call for Proposal for the fiscal year of 2007-2008, under the category of Innovative Research Topics for possible seed funding of 25K. The proposal has been approved by PATH and Caltrans, and a contract has been issued, with a target performance period of October 1, 2008, through September 2009.

According to the information posted on the website of Energy Information Administration (EIA) of the U.S. Department of Energy, the United States had approximately 21 billion barrels of proved reserves of crude oil in 2004, but consumed on average 21 million barrels of petroleum per day.<sup>21</sup> Although more conventional crude oil will be found in the United States and oil of lower grades can be refined, the 21 billion barrels of proven oil reserves could supply U.S. consumption for only 1,000 days. Currently, 60 percent of the oil consumed in the United States is imported from other countries.

The pre-industrial concentration of CO<sub>2</sub>, a major greenhouse gas, is approximately 280 parts per million (ppm); its current concentration is approximately 380 ppm. The CO<sub>2</sub> concentration has been steadily increasing in the past 40 years, as shown in Figure 30 and Figure 31.

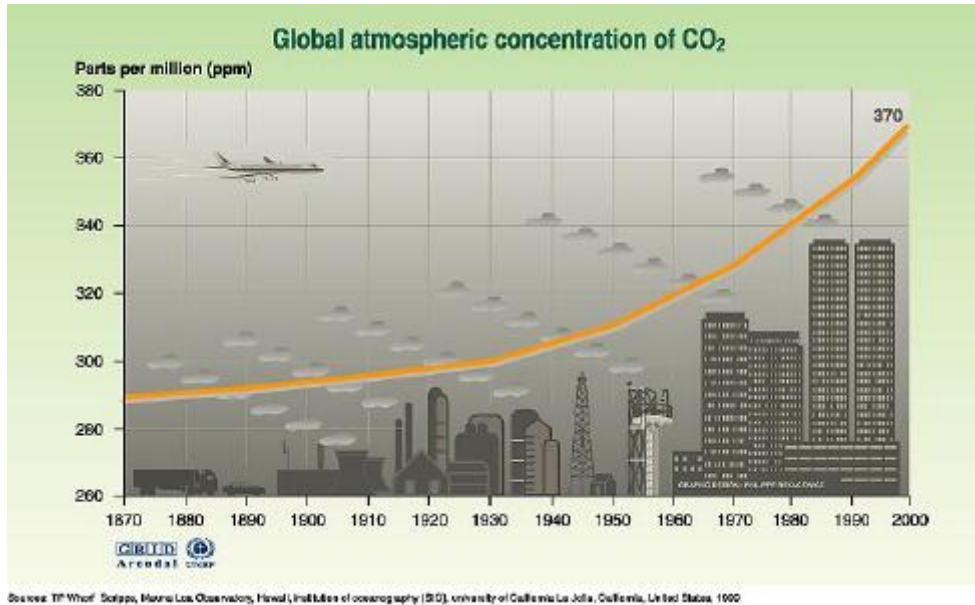


**Figure 30 Steady Increase of CO<sub>2</sub> concentration in the atmosphere (1959-1998)**

These figures do not include any predictions about the possible increases in energy demand and CO<sub>2</sub> concentration from the fast growth of some developing countries, such as Brazil, Russia, India, and China.

Public transportation may be one of the few sustainable transportation solutions for urban or suburban areas in the future. We believe that the proposed system provides real hope for the government and public to build an efficient, effective public transportation system for the many urban or suburban commuter corridors in the United States where right-of-way sufficient for a two-dedicated-lane BRT or light-rail system does not exist. In addition, for busy commute corridors that have sufficient right-of-way but do not have sufficient demand to warrant dedicating two mixed-use lanes to public transportation, the proposed system could be a useful intermediate step toward a two-dedicated-lane system because of its potential for facilitating transit-oriented development.





**Figure 31 Accelerated increase of CO<sub>2</sub> concentration (1870–2000)**

Specific examples can be found in the San Francisco Bay Area.

The right-of-way of an overwhelming majority of the corridor being considered for the East Bay BRT Project, which seeks to deploy a two-dedicated-lane BRT system between Berkeley and San Leandro along Telegraph Avenue and International Boulevard, is equivalent to seven traffic lanes, with a parking lane considered as equivalent to a traffic lane and one dedicated left-turn lane (for both directions) also considered as one traffic lane. This amounts to two lanes for through traffic for each of the two directions. However, the geometrical configuration of a bus stop of the two-dedicated-lane BRT system as sketched in the current plan requires a right-of-way width equivalent to four traffic lanes: two of the four lanes are dedicated for bus traffic and the other two allocated to accommodate passenger activities, one for each direction; left turning for each direction is accommodated within the construct of the four-lane configuration. This amounts to an almost 60 percent reduction of capacity for the non-BRT through traffic. If geometric symmetry is assumed, only one lane of through traffic will be allowed for each direction, and there will be space for parking on only one of the two curbsides. Corridor sections designated to accommodate such a bus stop may be recurrent bottlenecks for through traffic, and also nonrecurrent traffic bottlenecks during an accident or incident. The one-dedicated-lane BRT system to be studied and simulated in detail requires only a right-of-way width equivalent to two traffic lanes, instead of four, and allows four lanes of non-BRT through traffic, two in each direction. Its potential benefit is significant, enabling a BRT system dedicated for two-way bus traffic without reducing capacity for non-BRT through traffic.

The potential of the one-dedicated-lane BRT could also be significant for the El Camino Real corridor spanning San Francisco and San Jose if a dedicated BRT system is to be implemented along the corridor. The right-of-way of an overwhelming majority of the southern portion of the corridor is equivalent to nine traffic lanes. The one-dedicated-lane BRT system to be studied and simulated in detail allows six lanes of non-BRT through

traffic, three in each direction. Its potential benefit is as significant, enabling a BRT system dedicated for two-way bus traffic without reducing capacity for non-BRT through traffic. When demand for BRT has been built up, the one-dedicated-lane BRT system can be expanded easily to a two-dedicated-lane system. This future research project seeks to optimize the operating rules and simulate the system performance, in order to verify the feasibility of the one-dedicated-lane BRT system.

Other potential benefits of the proposed concept may exist and are worthy subjects for future study. For example, the dedicated lane or lanes may be open to non-BRT buses. However, the resulting operations will be more complicated. Other operational issues should be studied also, particularly those involving safety. For example, some of the passenger platforms may become visual barriers, making it difficult for a bus operator to see if a bus is coming from the opposite direction. Weather conditions will also create visibility problems. The proposed one-dedicated-lane operations should be supported by signals, gates, and other electronic warning devices that inform operators when another vehicle is approaching. This should be tested in the next phases. This issue becomes more important as headways are reduced, and if non-BRT buses are allowed to use the system.

This research developed geometric configurations that can support two-way bus traffic on one dedicated lane. These configurations must be developed further into detailed geometric designs for further feasibility study according to detailed standards.<sup>22</sup>

One reviewer suggested that a one-dedicated-lane BRT system and a one-dedicated-lane light-rail system can be two intermediate phases that can bridge an existing two-dedicated-lane BRT system and a two-dedicated-lane light-rail system to be constructed, minimizing the disruption to the transit traffic during the construction. The reviewer stated

Suppose a city is designing a two-lane BRT system with the idea that they will eventually want to convert it to LRT. Ordinarily, they would need to shut down the busway completely during LRT construction. But this research indicates that this may not be necessary. After the Phase 1 busway construction, Phase 2 could switch to one-lane bus operations while the other lane is converted to LRT. Phase 3 could switch to one-track LRT operations while the second lane is converted, and Phase 4 could be dual-track LRT operation. If a city wanted to plan this evolution in advance, how would it design its median busway in Phase 1? And how would this design evolve to accommodate each phase of construction?

This is an interesting idea and a worthy subject for future research.

## **SUMMARY**

This project has sought to identify and resolve major implementation issues and to assess the practicality and performance of the proposed system. A key issue is the crossing of buses traveling in opposite directions and the space such crossing requires.

The following are the most critical new issues for this project:

- how to accommodate buses crossing in opposite directions, which requires one additional lane beyond the one dedicated lane, without any negative impact on the traffic using the regular mixed-flow lanes
- how to accommodate passenger access, boarding, and alighting in a minimum amount of space
- whether such accommodation can be provided at enough locations at regular distance intervals so as to provide the same or similar level of service that is achievable by the conventional counterparts

The basic idea behind the proposed concept is simple. Bus crossing is accommodated on the otherwise unused or underused median space resulting from provision of the left-turn lanes. Although not necessary, some left-turn lanes can be sacrificed for bus stops. Crossing spaces can be placed strategically to achieve desired bus headway and travel time. As in the case of a two-dedicated-lane BRT system, bus speed profiles can be adjusted and transit signal priority employed to maximize adherence to the schedule.

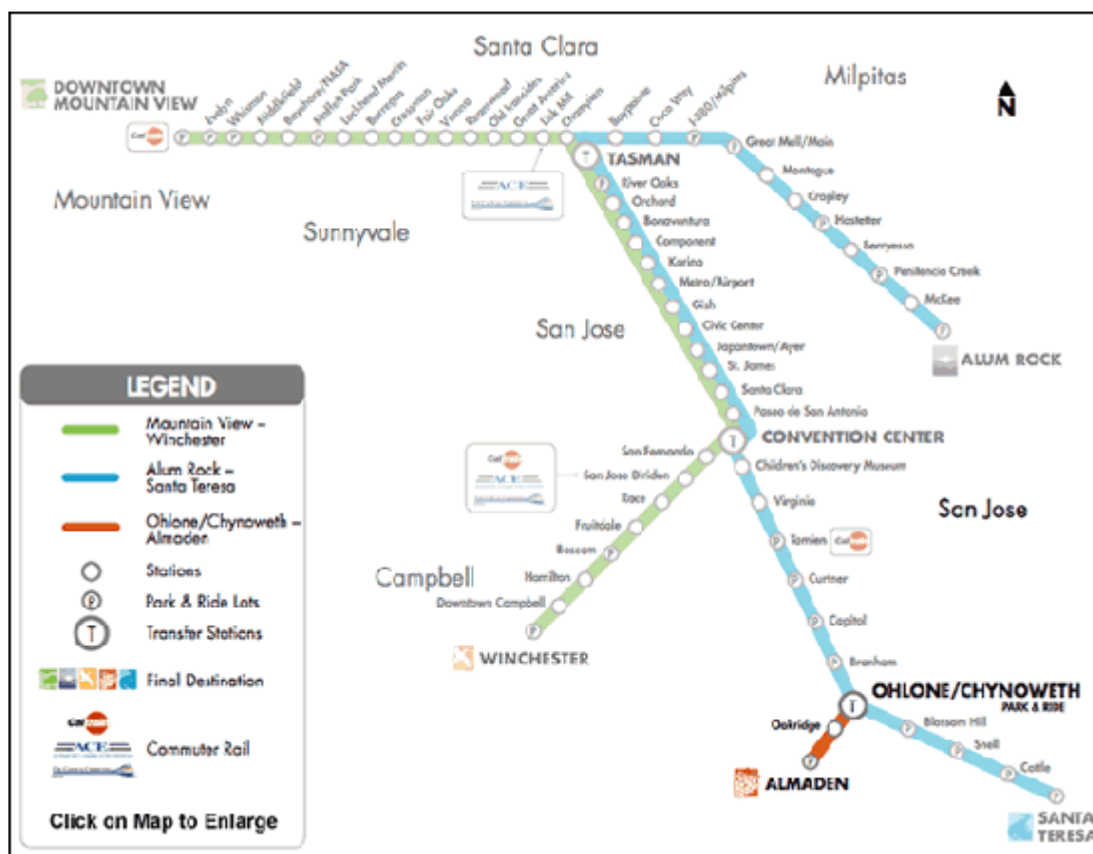
This project demonstrated the practicality of the proposed system with many conceptual design options and geometric-configuration sketches for the bus stop and crossing space, and with a deterministic study of the system performance in terms of travel speed, headway of operations, distance between two neighboring crossing spaces, and number of crossing spaces. To ensure practicality, it studied implementation of such a system on an existing corridor.

This project also proposed ways to implement a two-dedicated-lane BRT or light-rail system with minimum right-of-way width and ways to expand a one-dedicated-lane system to two dedicated lanes. All BRT or light-rail systems already implemented or intended for possible future implementation in the United States involve two dedicated traffic lanes. In addition, a space equivalent to four traffic lanes is dedicated to accommodate a bus stop. We proposed implementations of such two-dedicated-lane systems that require a space equivalent to only three lanes at a bus stop, based on two key ideas proposed for a one-dedicated-lane system. The three-lane requirement is particularly advantageous over its four-lane counterpart because many busy commuter corridors are served by a thoroughfare with a right-of-way that is equivalent to seven traffic lanes, with two traffic lanes for each direction, one parking lane for each direction, and one left-turn lane in the median used for the appropriate direction. Dedicating three lanes for the BRT or light-rail system still leaves two lanes per direction; dedicating four lanes results in either an asymmetric roadway geometry or no more than one lane for each direction. This project also proposed ways to expand the proposed one-dedicated-lane systems to two-dedicated-lane systems, as the demand for public transportation grows and dedication of an additional lane is accepted by the general public.



## APPENDIX A

### SANTA CLARA VALLEY TRANSPORTATION AUTHORITY (VTA) LIGHT-RAIL SYSTEM MAP





## ENDNOTES

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## ABBREVIATIONS AND ACRONYMS

BRT	Bus rapid transit
TOD	Transit-oriented development
EmX Green Line	Eugene-Springfield (Oregon) BRT
SPC	Speed-profile control
TSP	Transit signal priority
PATH	Partners for Advanced Transit and Highways
VTA	Valley Transportation Authority
NEXTOR	National Center of Excellence for Aviation Operations Research
MTI	Mineta Transportation Institute
SJSU	San José State University
HAIL	Human Automation Integration Laboratory



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## ABOUT THE AUTHORS

### DR. H.-S. JACOB TSAO

Dr. H.-S. Jacob Tsao received his BS in Applied Mathematics from National Chiao-Tung University in Taiwan in 1976, his MS in Mathematical Statistics from The University of Texas at Dallas in 1980, and his PhD in Operations Research from The University of California, Berkeley in 1984.

He worked as a software development engineer at Consilium, Inc. (currently an Applied Materials company) on computer-aided manufacturing for two years after his PhD studies. In the following six years, he worked for AT&T Bell Laboratories and Bell Communication Research as a systems engineer on large-scale software systems designed to automate circuit provisioning and capacity expansion planning for communication networks. He joined the Partners for Advanced Transit and Highways (PATH) Program of the Institute of Transportation Studies of University of California at Berkeley in 1992 and researched concept development and evaluation for intelligent transportation systems. He was a member of the research staff of National Center of Excellence for Aviation Operations Research (NEXTOR) between 1997 and 1999 within the same Institute.

Since 1999, he has been with San José State University, where he is Professor of Industrial and Systems Engineering and Director of Interdisciplinary Master of Science Program in Engineering. In the summers of 2004 through 2006, he led two-week study tours of Taiwan and China, as part of the Global Technology Initiative sponsored by the College of Engineering. In the winter of 2008, he participated in a two-week study tour of India, as part of the same initiative. He has taught courses in operations research, quality assurance, reliability engineering, information engineering, experimental design, and statistics. He has many technical publications, including more than 30 refereed journal papers and two books—*Entropy Optimization and Mathematical Programming* (1997) and *Testing and Quality Assurance for Component-based Software* (2003). Details can be found at <http://www.engr.sjsu.edu/jtsao>.

### DR. WENBIN WEI

Dr. Wenbin Wei is a faculty member in the Department of Aviation and Technology at San José State University. Prof. Wei received his MS with a concentration in Computer Aided Engineering and Management from Carnegie Mellon University in 1995, and his PhD with a concentration in aviation management from UC Berkeley in 2000. He worked as a postdoctoral researcher at both the California PATH program and the NEXTOR aviation research center from 2000 to 2001. He was a research analyst in the department of Operation Research and Decision Support at American Airlines from 2001 to 2003. He is currently a full-time assistant professor in the college of engineering and a research associate in the Mineta Transportation Institute in the college of Business at San José State University. Dr. Wei has also been a research associate at the San José State University Human Automation Integration Laboratory (HAIL) since 2005. Dr. Wei teaches a graduate course on airport planning and design for the Department of Civil Engineering; undergraduate courses on airport planning and management, and airline operation and management for the Department of Aviation and Technology; and two

graduate courses, logistics for the supply chain and advanced supply chain engineering, for the Department of Industrial and System Engineering at SJSU. He also worked for two years as a research consultant in the Department of Transportation of Jiangsu province, China.

Dr. Wei has extensive experience in applying advanced air traffic control technologies and system analysis for airport surface operations, through research projects both at NEXTOR at UC Berkeley and in the SJSU HAIL, including analysis of the impact of weather on airport capacity, quantifying the benefit of airport capacity expansion, building metrics to measure airlines' scheduling adaptation to airport expansion, workload analysis for the "big air" concept in the Joint Planning and Development Office's Next Generation Air Transportation System (NGATS) framework, and improvement of air traffic management in the terminal area through coordination of air traffic control in the air and aircraft movements on the ground.

### **MR. AGUS PRATAMA**

Mr. Agus Pratama received his BS in Industrial Engineering from Parahyangan Catholic University of Indonesia in 2005 and his MS in Industrial and Systems Engineering from San José State University in 2007. He is currently pursuing his MS in Computer Engineering with a concentration on software systems.

## **PEER REVIEW**

San José State University, of the California State University system, and the MTI Board of Trustees have agreed upon a peer view process to ensure that the results presented are based upon a professionally acceptable research protocol.

Research projects begin with the approval of a scope of work by the sponsoring entities, with in-process reviews by the MTI research director and the project sponsor. Periodic progress reports are provided to the MTI research director and the Research Associates Policy Oversight Committee (RAPOC). Review of the draft research product is conducted by the Research Committee of the board of trustees and may include invited critiques from other professionals in the subject field. The review is based on the professional propriety of the research methodology.





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